ENVIRONMENTAL AND DIAGENETIC STUDIES OF THE CLEVELAND IRONSTONE FORMATION OF NORTH EAST YORKSHIRE

by

Timothy M. Chowns

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PLATE 1 BRACKENBERRY WYKE: Type section of Cleveland Ironstone Formation.

PLATE 1

I N T R O D U C T I O N

INTRODUCTION

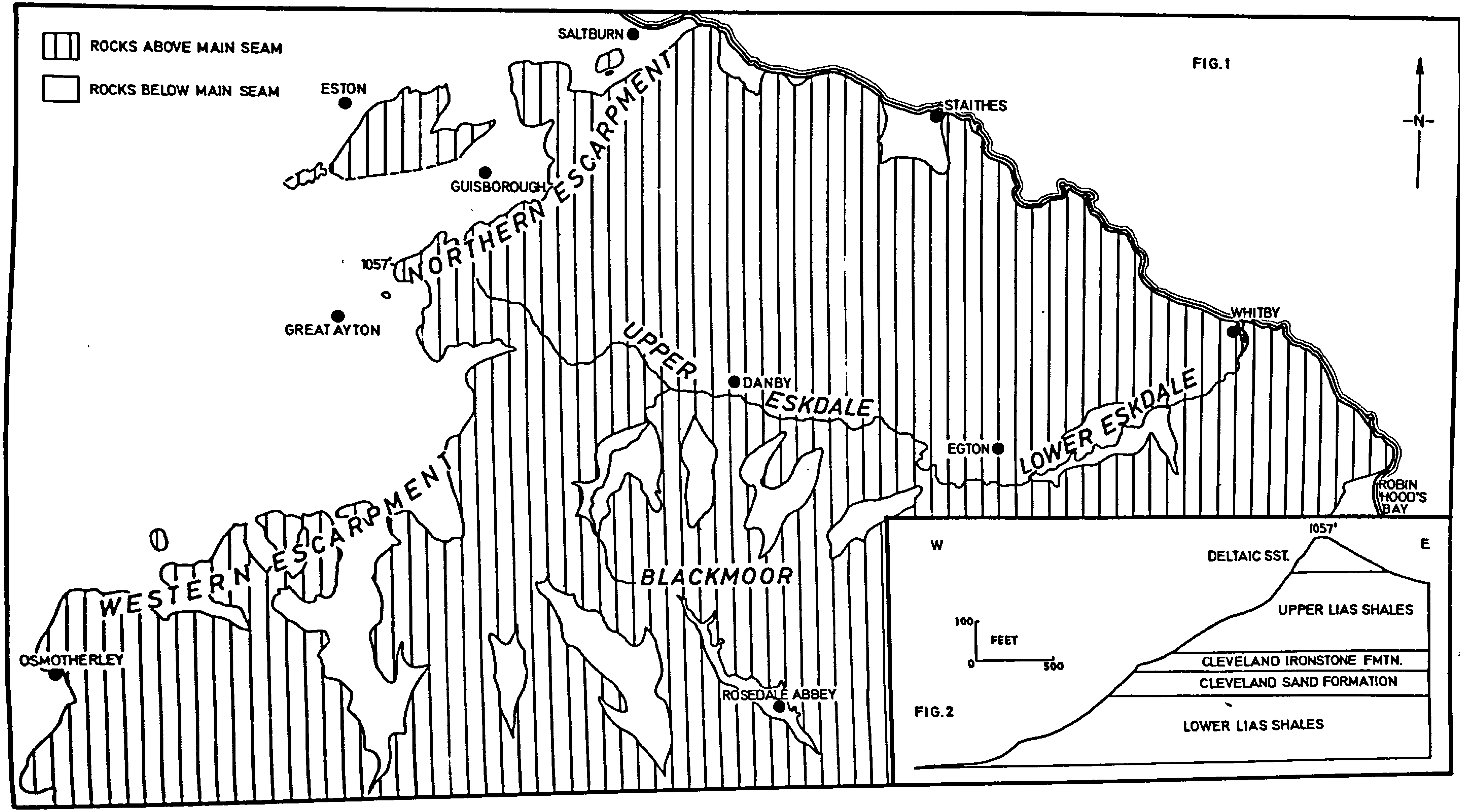
The Cleveland Ironstone Formation of North-East Yorkshire constitutes the topmost division of the Middle Lias. Palaeontologically it lies within the spinatum and upper margaritatus zones, occupying the whole of the Domerian with the exception of the stokesi subzone, which belongs to the underlying Cleveland Sand Formation. (For a discussion of this stratigraphic nomenclature see pages 15-16 ~~together with appendix A~~.)

Within the area covered by this investigation the Formation includes between 30 and 100 feet of shale and silty shale with siderite mudstone nodules, and subordinate oolitic iron ores. To this area the name Cleveland will be applied through these pages. Regarding the boundaries of this rather poorly defined region there is some disagreement (Rastall 1949, Hemingway 1966; pp. 8-9) and it is therefore proposed to use the name loosely in order to include the whole of North-East Yorkshire where outcrop evidence of the Ironstone Formation is available (fig. 1).

The most northerly outcrops occur on the north-westerly facing escarpment of the Cleveland Hills. At the foot of the escarpment Lower Lias Shales are found rising steeply to the Cleveland Sand Formation. The less resistant strata of the Ironstone Formation often weather back to form a small bench, by which they may be located along various parts

FIG. 1. CLEVELAND: GENERAL SETTING.

FIG. 2. (Inset) CROSS SECTION OF ROSEBERRY TOPPING.



of the escarpment. The Upper Lias Shales above are usually poorly exposed, but the Jet Rock is a prominent horizon, followed by the tips of the jet miners, which serve as a useful marker. The summit of the escarpment is provided by the sandstones of the Middle Jurassic. Southwards from the hills around Guisborough a gentle south-easterly dip carries the beds down to sea level at Staithes and Kettleness. At Whitby the top of the Middle Lias lies some 200 feet below sea level but is returned to the surface at Hawsker Bottoms by the Robin Hood's Bay Dome.

The dissection of the Eskdale and Cleveland domes by the River Esk and its tributaries once more reveals the Ironstone Formation in the area known as Blackmoor. On the north-western escarpment the beds reach a maximum elevation of 1,000 feet under Botton Head, on the crest of the Cleveland Dome, and then fall south-westwards until they become obscured under the drift in the neighbourhood of Osmotherley.

Outcrop information is therefore available in four main areas.

1. On the coast at Staithes, Kettleness and Hawsker.
2. Along the partly drift covered escarpment between Saltburn and Kildale including the outlying Eston, Upleatham and Hob Hills.
3. From the escarpment of the Cleveland Hills between Kildale and Osmotherley and from Bilsdale, Raisdale and Scugdale.
4. In the dales of Blackmoor (Baysdale, Westerdale, Danby Dale, the Fryup Dales, Glaisdale, Eskdale, Iburndale, Rosedale, Farndale and Bransdale), (fig. 1).

Additional evidence is drawn from the records of shaft sections and exploratory boreholes within the mining area, and from an examination of the workings at North Skelton Mine prior to its closure in February, 1964.

The geological mapping and location of exposures by the Geological Survey (1880-83) is very reliable, so that no mapping was necessary during this work. However all the available sections were re-examined, remeasured and correlated to provide the basis for the stratigraphic section of the thesis and the framework for the mineralogical and petrological description of the different sedimentary facies, the aim of the work being to determine the environmental setting and diagenetic history of the Cleveland Ironstone Formation and to compare and contrast it with other deposits of similar type.

A. HISTORICAL SUMMARY OF PROGRESS IN RESEARCH

The progress in geological knowledge of the Jurassic rocks in Yorkshire was followed by Fox-Strangways (1892, pp. 7-22) and the literature of the Yorkshire Lias reviewed chronologically by Tate and Blake (1876, pp. 5-11). More recently Dunham (1960) provided a comprehensive bibliography of the Yorkshire iron ore deposits, while Howarth (1955) reviewed the palaeontological studies of the Domerian in Yorkshire.

The first attempt to describe the geological structure of North-East Yorkshire systematically was made by Young and Bird (1822) who recognised in "the great beds of Alum Shale" the "Kettleness beds" and "Staiths Beds" as two distinctive horizons, between "the main bed of alum shale" above and the "lowest bed of alum shale" below. The correlation of the "Alum Shale" with the Lias in Southern England was made by Sedgwick (1826) and later by Phillips (1829, 1835) who replaced Young and Bird's (op. cit.) subdivisions by:-

Upper Lias Shale	c. 200 ft.
Ironstone and Marlstone Series	c. 150 ft.
Lower Lias Series	500 ft.

thus emphasising the similarities between the Liassic successions in Yorkshire and the Midlands. The amount of stratigraphic detail given was small but was greatly increased in the third edition in 1875.

Two short papers in 1836 are of interest as the first attempts to localise the fossils at their various horizons (Hunton 1840, Williamson 1840). Hunton's contribution is particularly valuable since it includes the first detailed measurements of the Middle Lias on the coast (at Rockcliff). In 1868 Simpson was to publish a similar table of strata at Hawsker Bottoms listing the fossils bed by bed.

In 1850 with the opening of the North Cleveland orefield a large amount of scientific information on the ironstone seams became available, in the publications of Marley (1857), Bewick (1861) and Bell (1863,'64). These works give information on the early history of the field, and its exploitation together with mine sections, maps and cross sections. The appended chemical analyses were largely derived from Crowder (1856, 1857).

The first hypothesis for the origin of the Cleveland Main Seam was presented at this time by Sorby (1886,7), who explained the iron enrichment in the Main Seam as the result of the diagenetic replacement of limestone; a theory which was to stand for over seventy years.

Tate and Blake's "Yorkshire Lias" (op. cit.) provides the first comprehensive description of the stratigraphy, palaeontology and economic potentiality of the Ironstone Formation both on the coast and inland, and has been an invaluable reference during the present work.

The primary mapping of Cleveland was carried out at a scale of

6" to 1 mile by the Geological Survey between 1852 and 1883. Both divisions of the Middle Lias were recognised, and the controversial Marlstone Series of Phillips was replaced by the Sandy Series. The sheet memoirs prepared by Barrow, Fox-Strangways and Reid (1885, 1886, 1915) have particularly detailed chapters on the Ironstone Formation, and although repeating much of the ground covered in "Yorkshire Lias" generally give more stratigraphic detail. On the whole Tate and Blake (op. cit.) give a more accurate assessment of the coastal sections, while the Survey improve on the inland exposures. Fox-Strangways' Memoir (1892) combines the information from the sheet memoirs with information from earlier sources; a very useful review and handbook to Cleveland geology.

The first petrological details of the Cleveland Main Seam apart from those of Sorby (1886, 1906) were given in an important paper by Stead (1910). After a microscopical examination by reflected light he concluded with Sorby that the deposit was originally an impure limestone. To this conclusion Burton also added his authority in 1913, in a useful discussion of sections taken on the southernmost limits of the orefield.

In a whole series of economic geology memoirs published at intervals as part of a complete survey of the mineral resources of this country, the Geological Survey continued the collection of scientific data accruing from the extension of the ironstone field.

With the exception of the work of Sorby and Stead these contain the only mineralogical and petrographic information on the ironstone seams to date. The first economic memoir to appear in 1856 (Smyth 1856) contained descriptions and analyses of iron ores assembled for the Great Exhibition of 1851 but only a short account of the Cleveland Ironstone. By the time of Wedd's work (Lamplugh et al. 1920) the whole of the orefield had been opened up and a large amount of stratigraphic detail was available from boreholes. Additional information on the minor seams and chemical analyses were provided through J. J. Burton. Eight years laterfollowed Hallimond's classic work (1928) demonstrating conclusively the primary origin of the Cleveland Ironstones and similar deposits elsewhere in England, and the significance of the mineral chamosite in the ores. The wartime pamphlet by Anderson (1942) was largely a review of the earlier Survey memoirs, but was later included in a larger memoir on the Liassic Ores (Whitehead et al. 1952) with some useful petrographic notes by Dunham.

The palaeontological framework for this study is provided by Howarth's work (1955), in which all the ammonite zones and subzones of the Domerian are recognised on the Yorkshire coast.

B. PROGRESS IN THE EXPLOITATION OF THE CLEVELAND IRONSTONES

The discovery and exploitation of the Cleveland ironstone coincided with the beginning of a revolution in the organisation of the British iron industry. The approaching exhaustion of the Coal-Measure ores, especially those in Northumberland and Durham, together with the tremendous savings in fuel consumption occasioned by the use of hot blast shifted the emphasis in location for the first time from the coalfields to an orefield outside the source of fuel. The success of Cleveland iron ore is therefore best understood against the economic and technological background of the time.

There are many descriptions of the history of mining in Cleveland, to which reference is made in Dunham's recent review (1960). Marley (1857), who gives the best informed account, cites several references to the discovery of ironstone in the Lias; one as early as 1790. Between 1811 and 1850, when the Eston Mines were opened, smelters continually rejected ore samples, sent from various parts of the field, for their examination. Both Young and Bird (1822) and Phillips (1829) describe the presence of ironstone on the coast but place no value upon it.

The earliest attempts to collect stone were made on the coast, where ironstone nodules could be taken from the scars; Bell (1864) records that in 1745 a smelter in Chester-le-Street was gathering nodules from Robin Hood's Bay, while between 1815-20 attempts were made to ship stone from between Peak and Saltburn. Several factors explain the failure to exploit the bedded ores commercially on a large scale during the first half of the century.

(i) The leanness of the ores was beyond the economic scope of the early nineteenth century blast furnace.

(ii) The inaccessibility of the field before the appearance of the railways increased transport costs out of proportion with the value of the ore.

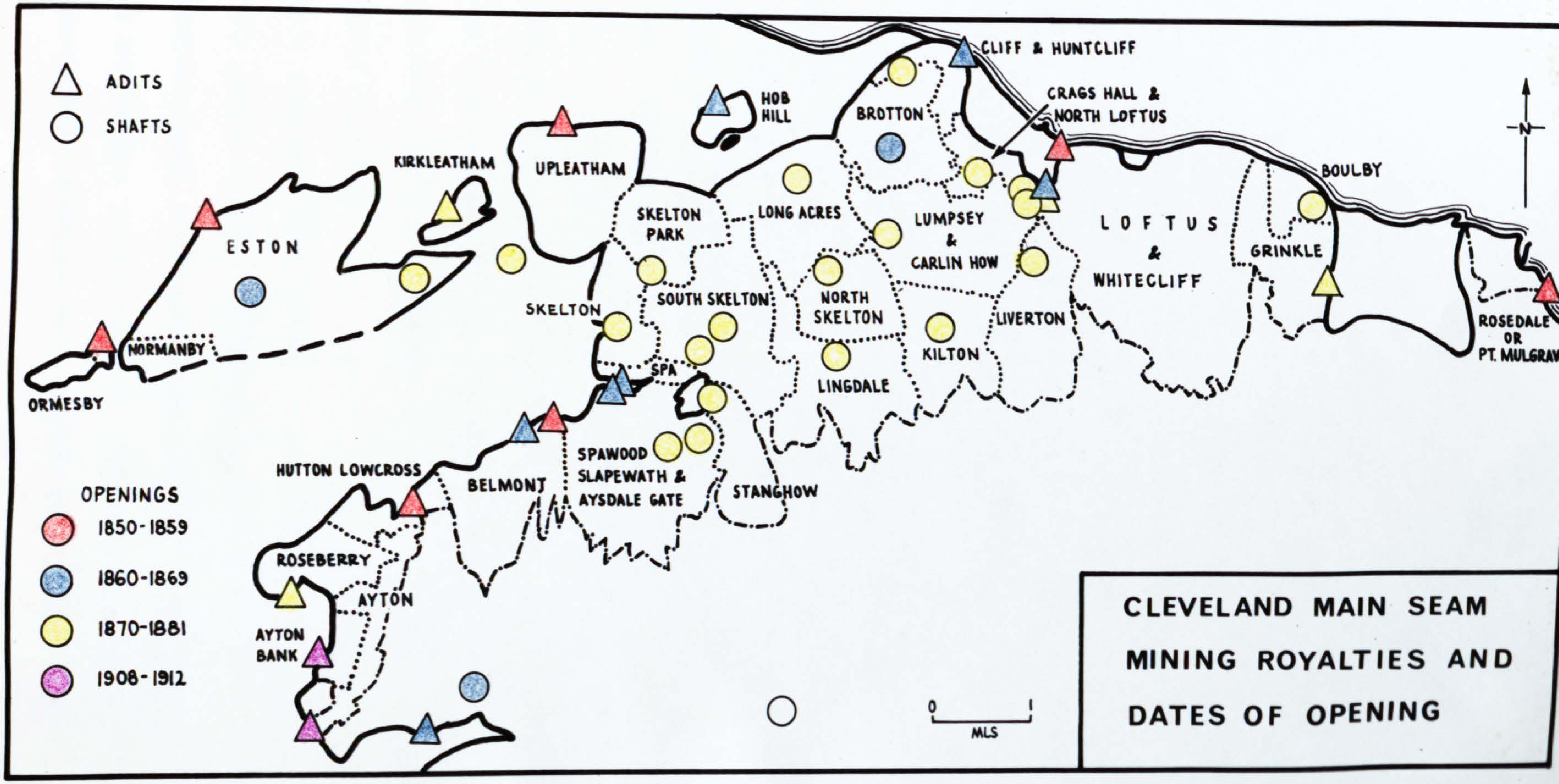
(iii) A misleading impression was created by the coastal exposures, examined by Young and Bird, and Phillips, while over much of the most valuable area, the outcrops were covered by drift.

The first commercial application of Cleveland Ironstone was made by the Whitby Stone Company, who subsequent to the opening of Stevenson's Whitby-Pickering railway (1836) leased mines at Grosmont, (Bewick 1861). The acceptance of this stone by the Birtley Iron Company in 1837 is explained by the greater accessibility of the area through the harbour at Whitby and as a result of the introduction of hot blast at the ironworks (Bell 1864). The success of this venture had several important effects. It encouraged a reappraisal of the coastal exposures at Staithes and Kettleness where quarrying operations were begun in 1838, only to collapse due to the difficulty of shipping the ore off such an exposed coastline. Secondly it demonstrated the value of the ore in Eskdale where further iron companies proceeded to take out royalties.

Among the first customers of the Whitby Stone Company were Messrs. Bolckow and Vaughan, to whom the opening of the northern part of the orefield at Eston was later due. In 1840 they had established rolling mills at Witton Park, Bishop Auckland ~~Middlesborough~~, in the expectation of ore from Weardale. In this expectation they were disappointed and were forced for a time to rely on a supply from Grosmont. However, the proximity of their works to the northern part of the orefield and the possibility of rail transport led to a renewed interest in this area. In 1848 the partners began collecting ore from the beach at Skinningrove and later in the same year took stone from a small mine close by. However, once again the greatest difficulty was experienced in shipping the ore and the Company were therefore induced to examine the escarpments at Upleatham and Eston where, on the 8th June, 1850, the Main Seam was discovered in some old quarries for road metal. The first trial pit was begun in August of the same year and by the 2nd September the first train load was dispatched. The public opening of the Eston Mines was on the 4th January, 1851 (Marley 1857).

The opening of the rest of the orefield is illustrated in figure 3. In 1854 Pease and Partners started quarries in Upleatham Hill, to be followed in the next two years, after the completion of the Middlesborough and Guisborough railway and its branch lines, by

FIG. 3.

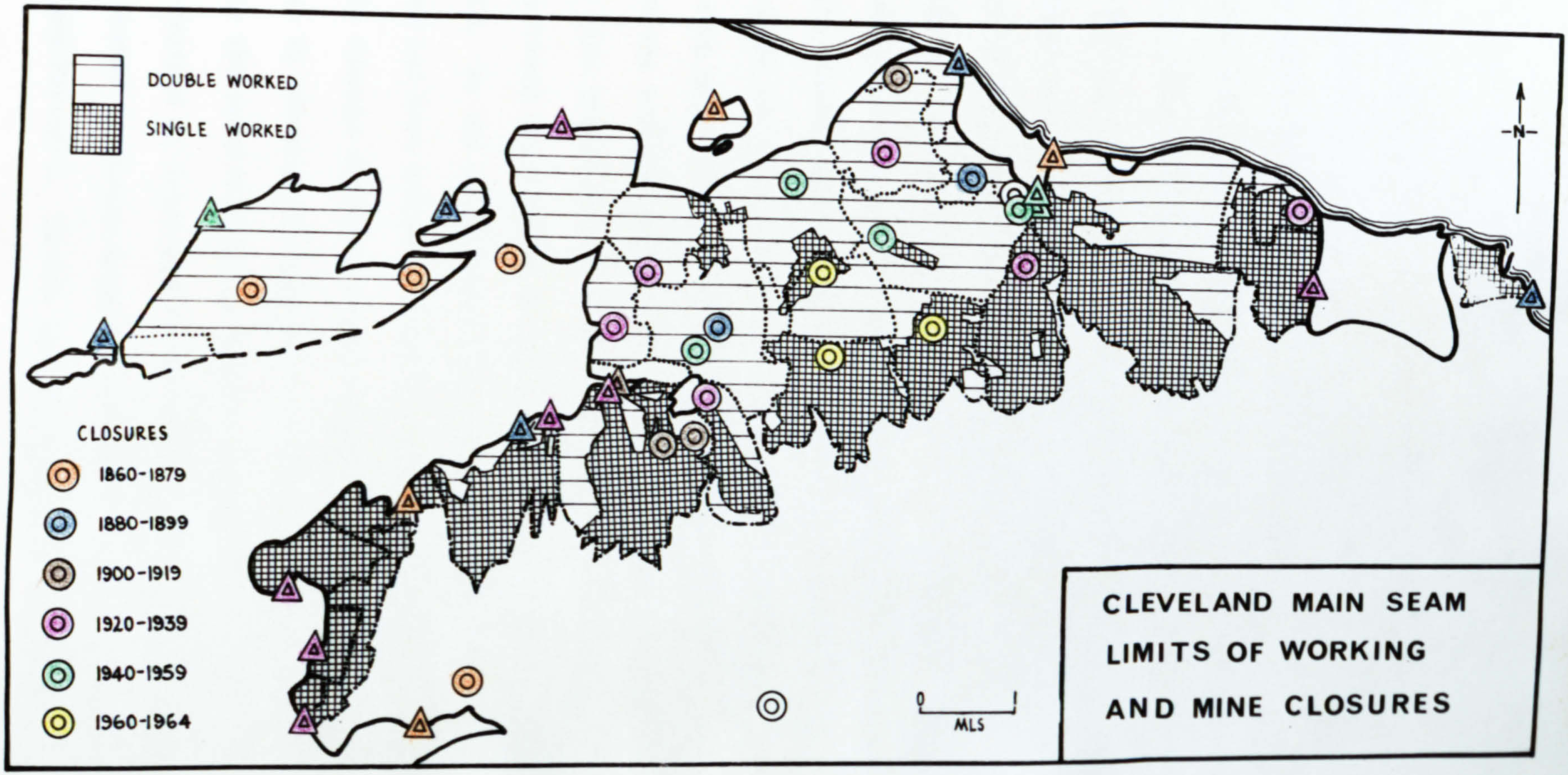


CLEVELAND MAIN SEAM MINING ROYALTIES AND DATES OF OPENING quarrying along the escarpment south of Guisborough as far as Roseberry Topping, and to the west of Eston at Normanby. The steepness of the escarpments, and in consequence the rapid increase in overburden, necessitated that quarrying was soon replaced in these royalties by adit mining. The first victims of the increased cost of mining were the Hutton Mines (1865) working poor stone towards the western boundary of the orefield. A western limit having therefore been placed on the field attention switched to the east centering in three main areas; the first south-east of Guisborough and along the Waterfall valley. Still further east the outcrops in the neighbourhood of Saltburn were tried and a third approach was made along the Skinningrove Valley.

By 1870 the majority of royalties on the outcrop had been leased and future development required costly shaft borings. Most shafts were therefore preceeded by exploratory boring. Between 1870-75 all the shafts in the Skelton area were completed including the costly and troublesome North Skelton Shaft -720'. (Steavenson 1874). With the completion of Lumpsey Mine in 1881 practically the whole of the present field was available for exploitation, and ore production had reached its maximum (fig.54).

The meteoric success of the industry between 1850 and 1880 is illustrated by the output of ore (fig.54) and by the population explosion in Middlesborough, which grew from a hamlet of 25 persons at the beginning of the century into a town of 5,709 in 1841 ~~when Bolckow and Vaughan first arrived at Witton Park~~, 40,000 in 1872 and 55,934 in

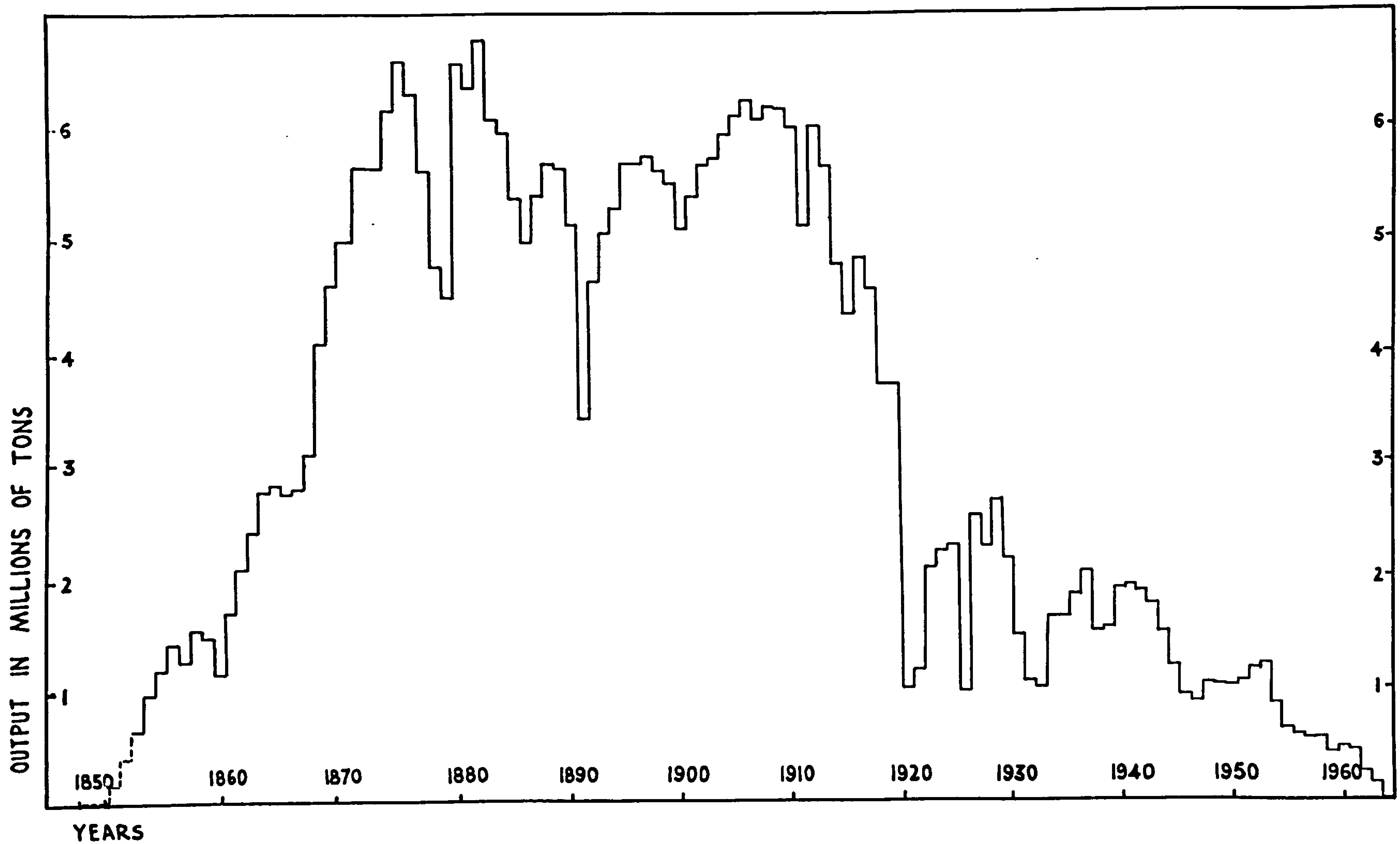
FIG. 4.


DOUBLE WORKED
SINGLE WORKED
-N-
CLOSURES
1860-1879
1880-1899
1900-1919
1920-1939
1940-1959
1960-1964
0
1
MLS
CLEVELAND MAIN SEAM
LIMITS OF WORKING
AND MINE CLOSURES

1881. The town was ideally situated to combine coking coal from Durham with Cleveland ore and to export through the Tees the cheapest pig iron in the world. (Roepke 1956, p. 55).

Between 1870 and 1914 the output from the field was maintained around the level of 5½ million tons per annum, but by the end of the war output was falling steeply. According to Lamplugh et al. (1920, p. 17) the thickest and best part of the Main Seam, north of a line from Guisborough to Skinningrove was approaching exhaustion, the future of the area lying to the south, in a belt averaging 2 miles in breadth. By 1920 this southerly belt of workings had been pushed as far south as was profitable, and it was open to speculation whether a further belt might be opened in the future. Figure ~~5~~ 4 shows the extent of mining in 1964 from which it is clear by comparison with Lamplugh's map (p. 15) that the workings were never extended. The gradual closure of the field is also illustrated in figure ~~5~~ 4. Among the first mines to close were short lived ventures at or beyond the southern limits of the main orefield. By the early part of this century many of the smaller royalties had been exhausted, the loss in output being compensated to some extent by renewed activity in the vicinity of Roseberry Topping. A steady increase in closures between the wars led to a further fall off in output, and to the consolidation of mining interests, so that by 1940 production centred on Eston and the group of mines around North Skelton royalty worked by Dorman Long, and Loftus, Whitecliff and Lingdale worked by Pease and Partners. In the twenty years following the war all

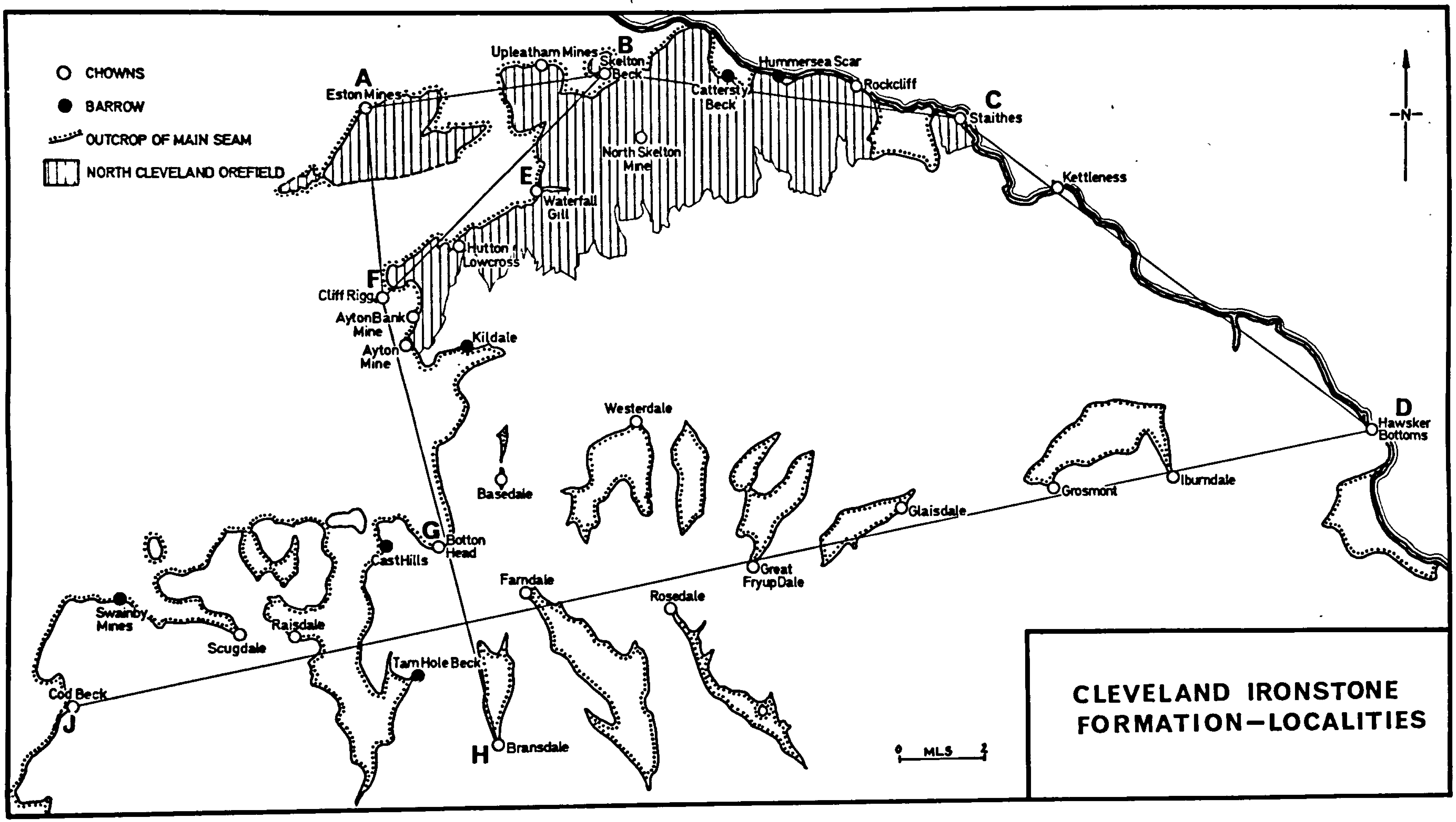
FIG. 5. OUTPUT FROM CLEVELAND IRONSTONE FIELD.



these mines were closed including the Eston Mines in 1950. The last mine to close was North Skelton on the 1st February, 1964. The total amount of ore extracted from the field between 1854-1964 (including the output from the Esk Valley and Rosedale) was 366,418,300 tons.

CHAPTER I STRATIGRAPHY

FIG. 6.



CHOWNS
BARROW
OUTCROP OF MAIN SEAM
NORTH CLEVELAND OREFIELD
N
A
Eston Mines
Upleatham Mines
B
Skelton Beck
Cattersty Beck
Hummersea Scar
Rockcliff
C
Staithes
Kettleness
North Skelton Mine
E
Waterfall Gill
Hutton Lowcross
F
Cliff Rigg
Ayton Bank Mine
Ayton Mine
Kildale
Westerdale
Basedale
D
Hawsker Bottoms
Grosmont
Iburndale
Glaisdale
Great Fryup Dale
G
Botton Head
Cast Hills
Farndale
Rosedale
Swainby Mines
Scugdale
Raisdale
Tarn Hole Beck
Cod Beck
J
H
Bransdale
0 MLS 2
CLEVELAND IRONSTONE FORMATION—LOCALITIES

I STRATIGRAPHIC NOMENCLATURE

In the course of mapping the Middle Lias in Yorkshire the Geological Survey divided the succession into two parts, the "Sandy Series" below and the "Ironstone Series" above, following similar subdivisions by Young and Bird (1822) and Phillips (1829). In modern stratigraphic nomenclature these two divisions rank as formations of the Middle Lias Group. Although Young and Bird's "Staiths Beds" and "Kettleness Beds" have priority over the names adopted by the Geological Survey (1882) the latter are better established. In appendix A the use of the names Cleveland Sand Formation and Cleveland Ironstone Formation is recommended.

The Cleveland Sand Formation - lies outside the main scope of this thesis but will be referred to in passing.

The Cleveland Ironstone Formation The base of the Formation is drawn at the top of the Osmotherley seam (bed 0 Staithes), and the top above bed 51 Staithes. The lower boundary coincides with the biostratigraphic division between the *stokesi* and *subnodosus* subzones, and the upper with the Pliensbachian-Toarcian boundary (Dean et al. 1961).

The subdivision of the Formation is best illustrated with reference to the type section at Staithes, where the succession is conveniently divided into members by the six ironstone horizons. (See Table 1).

Table 1

Palaeontological subzones	Succession			Stratigraphic members	
Pleuroceras hawskerense	shales	48-51		hawskerense beds	Cleveland Ironstone Formation
P. apyrenum	Main Seam	44-47		apyrenum beds	
	shale	43			
	Pecten Seam	31-42			
Amaltheus gibbosus	shale	30	upper	gibbosus beds	
	2 ft. Seam	29	middle		
	shales	26-28			
	Raisdale Seam	25	lower		
	shales	22-24			
A. subnodosus	Avicula Seam	20-21		subnodosus beds	
	shales	1-19			
A. stokesi	Osmotherley Seam	0		stokesi beds	
	shales, siltstones and sandstones				

Bed numbers correspond with the detailed section given in appendix ~~B.~~ I

The outcrop of each subzone at the type exposure is shown by Howarth (1955, plate 12). Further stratigraphic detail of this and other measured sections are given in enclosures 1-3 and in appendix ~~B~~I. The location of these sections may be found in figure 6.

II SUBNODOSUS BEDS

The *subnodosus* subzone comprises the beds from the top of the Osmotherley seam up to and including the *Avicula* Seam, and is the least well exposed member of the Formation. Enclosure 1 summarises the stratigraphical information available at outcrop. A number of boreholes pass through the member, but unfortunately the horizon of the Osmotherley seam is never recognised and the other details are unreliable. The subzone is dominated by grey shales and silty shales with siderite-calcite mudstone nodules, a gradual upward passage through shales into silty shales being recognised in all the exposures. This sequence is truncated by the *Avicula* Seam.

A. OSMOTHERLEY SEAM

1. Nomenclature

The existence of an ironstone seam beneath the *Avicula* seam, has not been generally recognised previously, although the horizon of the seam has been aluded to in the exposures at Hawsker Bottoms (Tate and Blake 1876, p. 109 bed 13; Howarth 1955, p. 155 bed 18), Staithes (Tate and Blake op. cit. p. 107 bed 17; Barrow 1888, p. 17; Howarth op. cit. p. 158, bed 26), and Skelton Beck (Barrow op. cit. p. 20). It has yielded both *A. subnodosus* and *A. stokesi* (Howarth op. cit.) but is probably best ascribed to the *stokesi* subzone, although it is included in the description of the *subnodosus* beds for convenience.

This seam has now been recognised in a further ten exposures and named the Osmotherley Seam from its thickest development in the neighbourhood of that village.

2. Recognition

The appearance of the fossiliferous flaggy siltstones of the Cleveland Sand Formation within ten feet beneath the seam is a useful criterion for its field identification, and immediately separates it from the *Avicula* Seam, with which it shares a similar lithology and trace fossil texture. However, with the exception of the exposures at Nun House, Over Silton and Cod Beck, Osmotherley, where the seam was confused with the *Avicula* Seam by the Geological Survey (Fox-Strangways et al. 1886) it is always inferior in thickness to the latter.

Characteristically the seam is divided into two parts.

(ii) Fine grained argillaceous siderite mudstone non-oolitic 0 - 3".

(i) Shelly oolitic siderite mudstone, often with green oolite lenses 0 - 1' 1".

3. Lateral Variation

Although the Osmotherley Seam has escaped notice, it is probably widely developed throughout Cleveland; it has been recognised in all the exposures where the base of the Ironstone Formation has been examined with the exception of Rockcliff. It reaches its maximum thickness on the western escarpment (1'4" at Nun House, Over Silton; 1'2" at Cod Beck, Osmotherley), where the lower oolitic portion of the seam is particularly well developed. Elsewhere the seam has never been seen to exceed nine inches. On the foreshore at Staithes and Hawsker, and inland at Grosmont the same division is present, but the lower oolitic part is much thinner; at Staithes no more than a trace, 2" at Hawsker and Grosmont.

4. Conclusions

The importance of the Osmotherley Seam lies in showing that even at the end of stokesi times the necessary conditions for oolitic ironstone formation were present in Cleveland. The seam has no economic value within this area, however.

B. SUBNODOSUS SHALES

1. Type Section

The subnodosus shales are 20'10" thick in the cliffs at Staithes and may be examined in detail on the foreshore. The Osmotherley Seam is overlain by medium grey silty shales (unit (i) enclosure 1) which pass rapidly upwards into a fossiliferous light grey silty shale, with prominent round concretions (unit ii). Above, medium grey silty shales pass into dark grey pyritic shales and then back into medium and light grey silty shales (unit iii). The predominant shale colour depends on the admixture of the silt and clay fractions, the original sedimentary lamination having been almost completely destroyed by the trace fossil Chondrites (plate 2). Anhedral pyrite occurs abundantly, disseminated through the shales, especially in the darker shales, and in association with the larger burrows. It may also occur as a replacement of ammonite and lamellibranch shells and in the septarian cracks of oblate siderite-calcite mudstone nodules, which occur at several horizons. The light grey silty shales at the top of this unit are interrupted by two prominent conglomerate horizons. The first horizon (unit iv) contains pebbles and cobbles of laminated calcareous siltstone set in a matrix of shelly limestone, largely comprised of Entolium shells. Although in some cases the pebbles may have been soft at the time they were incorporated, in most cases they are well rounded and show no sign of plastic deformation. In addition derived nodules, some with septarian cracks, occur. This horizon clearly marks an important hiatus in deposition and throws light on the penecontemporaneous formation of concretions. Just over a foot and a half of fossiliferous light grey silty shale (unit v) intervenes between this bed and the second conglomerate (unit vi) which is closely similar to it. Both conglomerates and the intervening shale have been the site of extensive carbonate segregation. The shale contains large oblate and tabular siderite mudstone concretions, which envelop the conglomerates above and below. The patchy development of unit vi and the conglomeratic nature of the base of the *Avicula* seam indicates a further hiatus before the deposition of the ironstone (see fig. 9).

2. Lateral variation

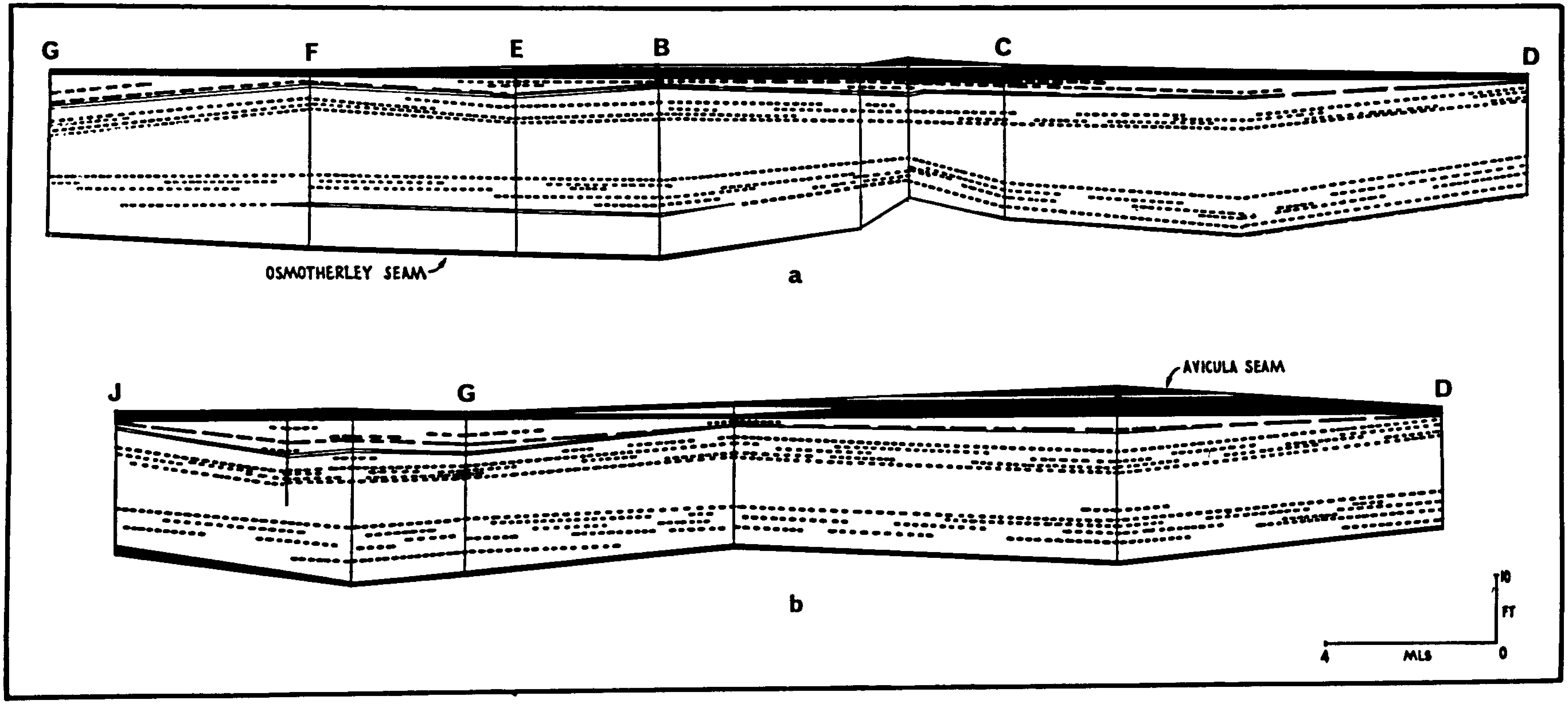
In the course of the 66 miles of cross-section illustrated in figure 7 the *subnodosus* shales show some variation in thickness, but little change in lithology.

a) Thickness

From a maximum observed thickness of 27'0" at Skelton Beck the beds appear to thin progressively south-eastwards along the coast and south-westwards along the escarpment (fig. 7a). However, there is a long gap between the sections at Staithes and Hawsker so that this impression may be misleading on the coast. The thickness of the shales at Hawsker is only 18'4", but followed westwards (fig. 7b) they thicken in the vicinity of Grosmont and continue thus as far as Raisdale, where a thickness of 24'5" was recorded. Within 6 miles, however, at Cod Beck, Osmotherley, they are reduced to 18'6".

Two different causes may account for these changes. In part they reflect original depositional variations, for instance the thickening within units i and iii is probably depositional; and in part they result from penecontemporaneous erosion. Three erosive horizons have already been noted in the type section. The lower horizon (unit iv) may be followed in an *Entolium* shell bed which appears at Rockcliff and in many other localities immediately beneath a laminated

FIG. 7. CROSS SECTIONS OF SUBNODOSUS SHALES



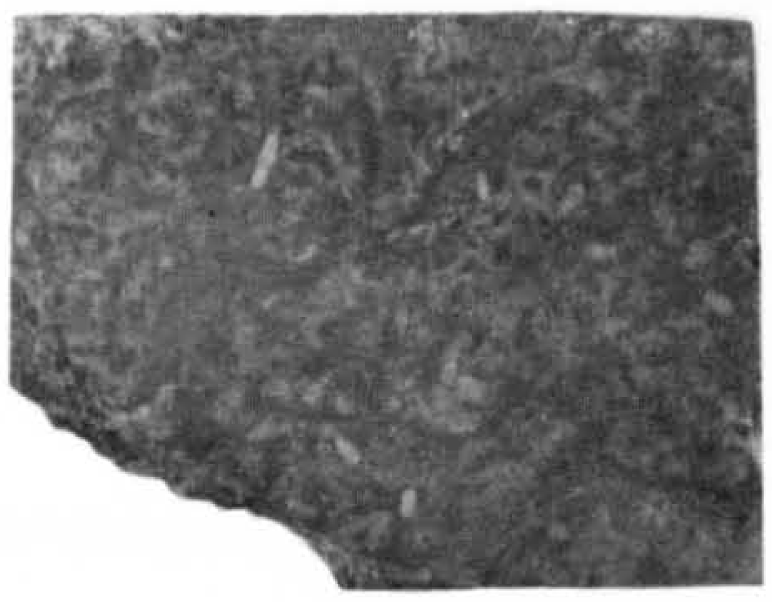
siltstone, not represented at Staithes. The base of this shaly siltstone probably indicates a break in deposition throughout the area, accompanied by local erosion. The succeeding conglomerate can be traced beneath the *Avicula* seam in the sections at Rockcliff and Skelton Beck, but is then truncated by the more important disconformity beneath the conglomeratic base of the *Avicula* seam, to which much of the attenuation of the *subnodosus* shales may be attributed. The extent of this denudation may be measured by the separation between the base of the seam and the laminated siltstone (unit iv). In the thick sections at Skelton Beck, Cliff Rigg, Botton Head and Raisdale, unit v is well preserved but at Hawsker it was almost entirely removed penecontemporaneously.

b) *Facies*

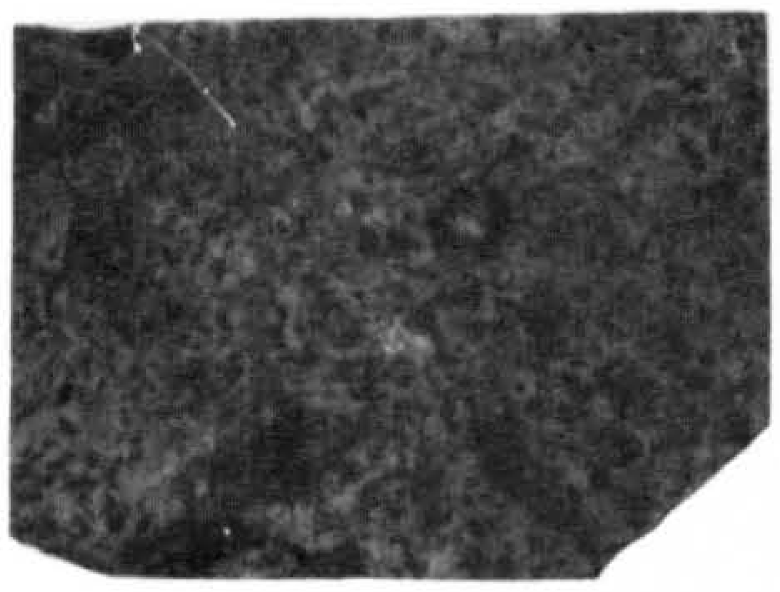
The same upward passage from dark grey shale into light grey shale, with the ubiquitous *Chondrites*, is apparent in all the sections in the subzone. Apart from the local appearance of silty shale in unit ii there is no evidence of a major change in facies such as that envisaged by Fox-Strangways et al. (1886). This observation was based on an erroneous correlation between the shales of the *subnodosus* beds and the *stokesi* siltstones ~~(see page)~~.

Even the siderite-calcite mudstone nodules reappear at the same horizons. In particular they are associated with the siltier shales, probably because the proportion of calcium and iron increase with

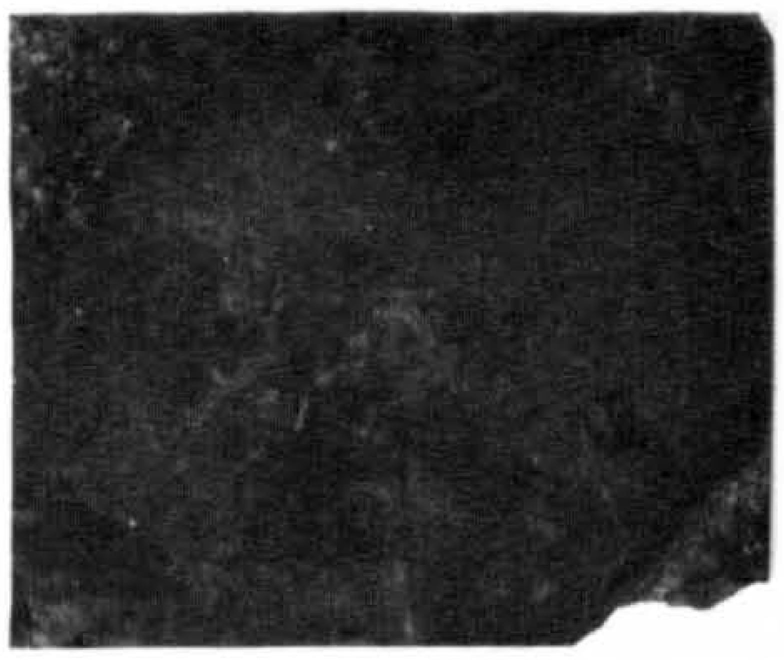
PLATE 2 Colour and succession of subnodosus shales, Staithes.



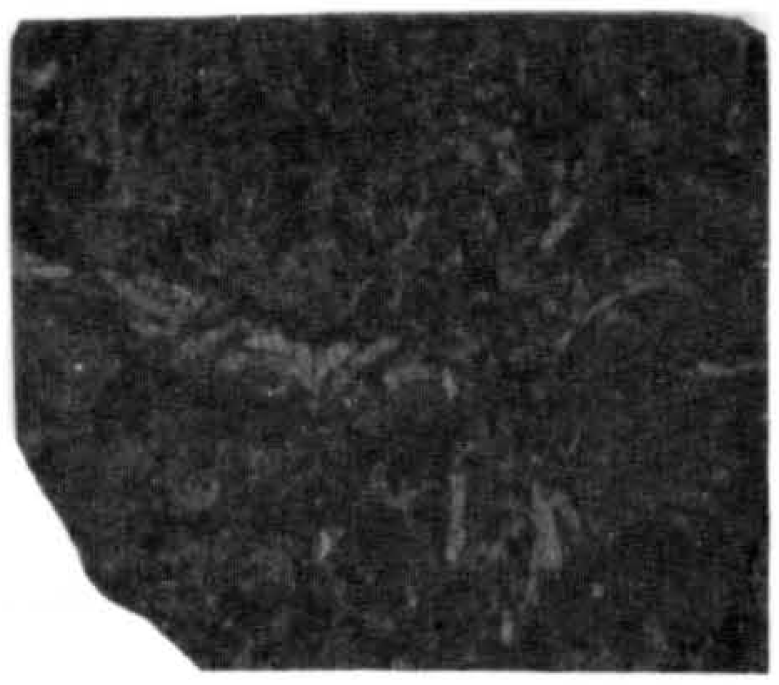
bed 16
light grey



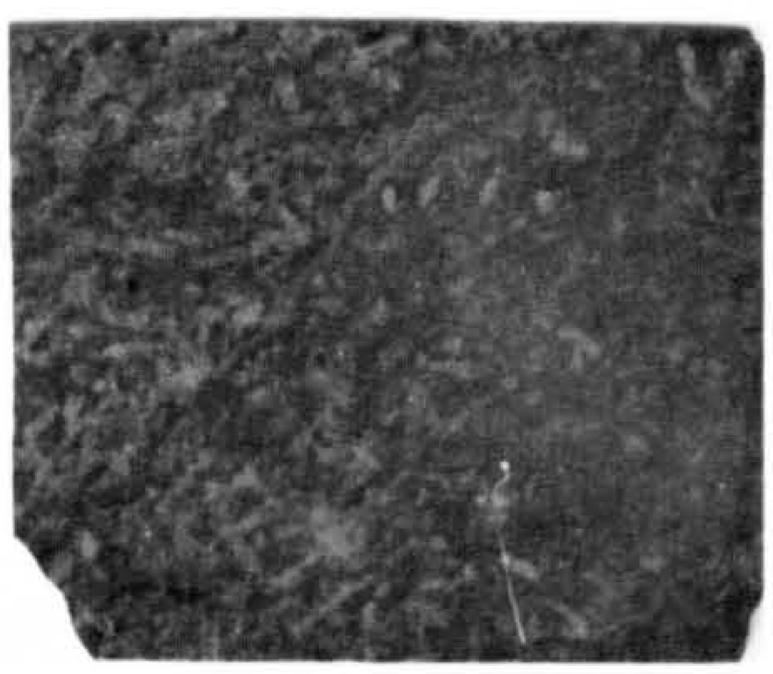
bed 10
medium grey



bed 7
dark grey



bed 3
medium grey



bed 1
light grey

subnodosus shales

PLATE 2

the silt fraction, but also possibly because segregation is favoured by the coarser grain size. The question of diagenesis will be discussed in further detail elsewhere (page 155).

3. Palaeontology and Palaeoecology

Where the succession can be examined in detail, on the foreshore at Staithes and Hawsker it is seen to be fairly fossiliferous, but away from the coast collecting is much more difficult owing to limited exposure. The richest fauna is found within the nodules; unit ii Staithes is particularly fossiliferous (see Tate and Blake 1876, p.108). Outside the nodules the fauna has been largely destroyed by decalcification. The shell beds (units iv and vi) are also very fossiliferous. A list of the common fossils is given in Table 2, but for greater detail Tate and Blake (1876, pp. 115-117) and Howarth (1955) should be consulted. From the table the predominance of lamellibranchs is evident. However, the only comprehensive study of this group in the Middle Lias is by Tate and Blake (op. cit.) and the nomenclature is in need of revision. Apart from the nektonic ammonites the fauna may be divided into two main groups; the epifauna and the infauna, (Peterson 1913, p. 15). The epifauna includes vagile species (P. equivalvis, O. inequivalvis, L. acuticostata),& sessile types such as Ostrea and Entolium, which are usually found disarticulated. Of the vagile forms O. inequivalvis, and L. acuticostata occur throughout the succession, while P. equivalvis together with E. lunularis and Ostrea occur in the higher energy

Table 2.

Ammonites

Amaltheus margaritatus

A. striatus

A. subnodosus

Belemnites

Lamellibranchs

Cardita multicostata

Ceratomya petricosa

Entolium lunularis

Gresslya sps.

Leda subovalis

Limea acuticostata

Modiolus scalprum

Ostrea sp.

Oxytoma inequivalvis

Protocardia truncata

Pseudopecten equivalvis

Gastropods

Amberleya (Encyclus) sps.

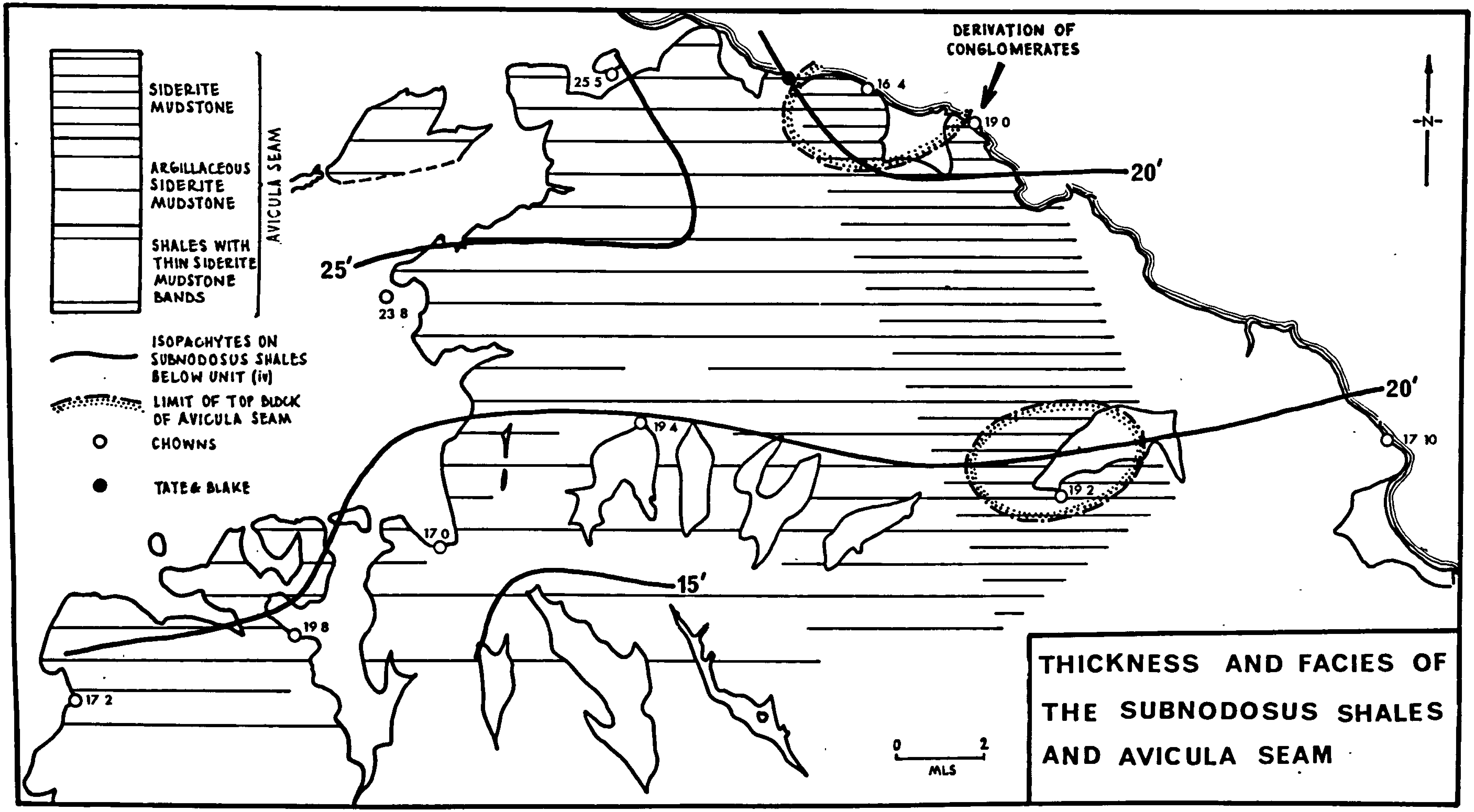
deposits (units ii, iv and vi). The remaining lamellibranchs were probably infaunal, although only the deep burrowing Gresslya remains in its position of life. In every other case it is clear that the shells accumulated by gentle winnowing of the sediment, accompanied by a certain amount of disarticulation. On the whole, however, the infaunal species are more commonly articulated than the epifaunal species. By analogy with recent bottom communities (Thorson 1957) the infauna probably comprised both deposit and suspension feeders. Like the modern Mya, Gresslya was probably a suspension feeder and also possibly Protocardium, which occurs most abundantly within the siltier shales. A large proportion of deposit feeders is indicated by the grazing burrow (fodinichnia) Chondrites (Seilacher 1967). L. subovalis was possibly among the deposit feeders.

In summary the fauna is exactly what one might expect in a silty mud, marine environment; a large infauna within the shales and a greater proportion of epifaunal species in the shell beds (Purdy 1964).

4. Environment of deposition

The lithology and fauna of the subnodosus shales are both consistent with deposition in a sublittoral (neritic) environment, (Hedgepeth 1957). The strong mottling of the shales by Chondrites, which is one of the most important features of the lithology also indicates relatively slow deposition in a sublittoral environment (Moore and Scruton 1957). The upward passage from shales into silty shales,

FIG. 8.


SIDERITE MUDSTONE
ARGILLACEOUS SIDERITE MUDSTONE
SHALES WITH THIN SIDERITE MUDSTONE BANDS
AVICULA SEAM
ISOPACHYTES ON SUBNODOSUS SHALES BELOW UNIT (iv)
LIMIT OF TOP BLOCK OF AVICULA SEAM
CHOWNS
TATE & BLAKE
DERIVATION OF CONGLOMERATES
N
25 5
16 4
19 0
20′
25′
23 8
20′
19 4
17 10
19 2
17 0
15′
19 8
17 2
0
2
MLS
THICKNESS AND FACIES OF THE SUBNODOSUS SHALES AND AVICULA SEAM

together with the evidence of erosion on non-deposition near the top of the succession, is suggestive of shallowing water, probably resulting from a gradual infilling of the basin of deposition.

In assessing the thickness variations, both original depositional thickness and the extent to which this was reduced by penecontemporaneous erosion must be taken into account. In figure 8 isopachytes have been drawn tentatively on the strata between the Osmotherley seam and unit iv in an attempt to show the original deposition variations. An east - west trend is indicated, with a zone of thick sedimentation extending from the vicinity of Guisborough eastwards to the coast at Whitby, which might be interpreted as a shallow depositional trough. The section from Hawsker to Cod Beck (fig. 7b) lies close to the strike of this depression, while the sections from Skelton Beck to Hawsker and Botton Head (fig. 7a) cross the axis.

C. AVICULA SEAM

1. Nomenclature

The name Avicula seam was introduced by Marley (1857, p. 181) for the lowest seam in the mines at Grosmont, from the prevalence of Avicula cynipes (now Oxytoma cygripes). With later authors (e.g. Bewick 1861, p. 45; Pratt 1861; Horton 1864; Pratt 1907) he ascribed to the view that it was equivalent to the Bottom Block of the Main Seam of North Cleveland. Later Tate and Blake recognised that it was "palaeontologically related to the upper margaritatus beds"

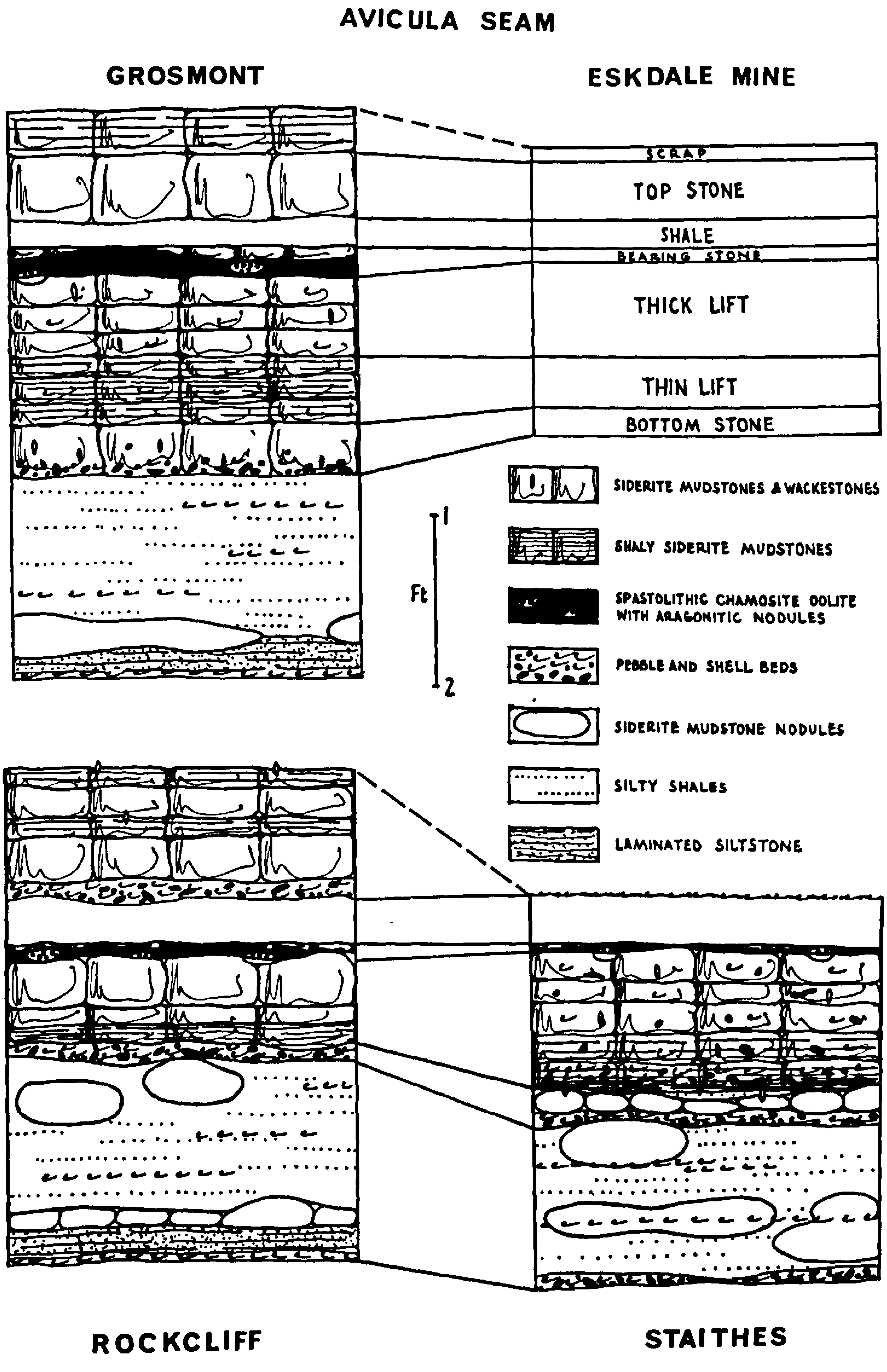

AVICULA SEAM
GROSMONT
ESKDALE MINE
SCRAP
TOP STONE
SHALE
BEARING STONE
THICK LIFT
THIN LIFT
BOTTOM STONE
SIDERITE MUDSTONES & WACKESTONES
SHALY SIDERITE MUDSTONES
SPASTOLITHIC CHAMOSITE OOLITE WITH ARAGONITIC NODULES
PEBBLE AND SHELL BEDS
SIDERITE MUDSTONE NODULES
SILTY SHALES
LAMINATED SILTSTONE
1
Ft
2
ROCKCLIFF
STAITHES

FIG. 9.

(1876, p. 114), but equated it with the Bottom Seam on the coast (2 ft. Seam). It remained to Barrow (1888, p. 30) in a comparison of the successions in Eskdale and on the northern escarpment to show the true stratigraphic relations of the seam.

2. Recognition

Where good stratigraphic and palaeontological control is present, as on the coast, the *Avicula* seam may be recognised by its position at the top of the *subnodosus* subzone. With the exception of the Hawsker section, the conglomeratic base of the seam always rests upon reworked light grey silty shales, which characteristically develop some of the largest siderite mudstone nodules in the succession. It is directly overlain by dark grey fissile shale at the base of the *gibbosus* subzone. The lithology and thickness of the seam in three important localities (Grosmont, Staithes and Rockcliff) is illustrated in figure 9.

The *Top Block* is only of local occurrence. Of this the "top stone", an oolitic siderite mudstone was mined at Grosmont but the shaly pyritic "scrap" was discarded.

The *Bottom Block* comprises poorly oolitic siderite and shaly siderite mudstone in several 'lifts', and a conglomeratic "bottom stone". The name "bearing stone" was applied to a green pyritic spastolithic chamosite oolite, which is a prominent feature in several localities (Grosmont, Staithes, Grinkle, Rockcliff, Raisdale, Scugdale).

3. Lateral variation

In the majority of exposures the Avicula Seam comprises little more than a foot of shaly siderite mudstone (see figs. 6 & 8) but there are two exceptions. The first is in Eskdale, in the vicinity of Grosmont, where between 1836-92 and again during the First World War the seam was exploited commercially. Here it was found in two blocks (fig. 9a,b) totalling up to 3'10" of ironstone separated by 2" - 4" of shale. It was workable as far west as Glaisdale Mine (fig. 8) and was tried to the east of Sleights Bridge. In the shaft of the Esk Valley Mine, south of Grosmont, it had thinned to about 2 ft., and a similar deterioration was reported north of the village (Anderson 1942, p. 5). In two exposures further west, in Rosedale and Westerdale, the seam is represented by two thin pebbly siderite mudstone horizons separated by shale, being the probable equivalents of the Bottom Block.

In the exposures at Rockcliff (fig. 9c) and Grinkle Mines the seam is again found in two blocks and appears to have been tried at the last locality. At Rockcliff there is 1'1" of ironstone in the Bottom Block and 1'6" in the Top, separated by 7" shale, while at Grinkle 1'6" in the Bottom Block but only 9" in the Top separated by 9" shale. Only a mile further east at Staithes the Top Block has disappeared altogether, although 8" of the middle shale remains with a thin pebble and shell horizon at the top (fig. 9d). To the north-west the Top Block seems to have been present in the Hummersea section (Tate and Blake 1876,

p. 105) but is absent once again in the sections at Skelton Beck and Waterfall (fig. 8). The Top Block, therefore, appears as a remnant, truncated by erosion during the subnodosus-gibbosus interval. The more important remnant at Grosmont is probably of the same origin, but the evidence is not as convincing; the top of the seam is conglomeratic and the "scrap" was apparently missing from some sections.

At Skelton Beck, Raisdale, Scugdale and Cod Beck the Bottom Block remains entire, but at Cliff Rigg and Botton Head, penecontemporaneous erosion removed the top few inches, while at Hawsker all but the basal conglomeratic portion were removed.

As a result of this denudation it is difficult to reconstruct the original facies and thickness relations of the seam. The poorest stone occurs in the exposures at Rosedale and Westerdale, where the seam is largely shale. Further west there is a slight improvement with the incoming of shaly siderite mudstone in the Bottom Block, but the most marked improvement takes place in an easterly direction, culminating in a belt between Rockcliff and Grosmont (fig. 8). How far this amelioration continued, in the strata which were removed by pre-gibbosus denudation, is difficult to say. The stone at Sleights Bridge was said to have been poor (Anderson 1942, p. 13) and may place an eastward limit to the improvement.

4. Palaeontology and Palaeoecology

In common with the ironstone seams yet to be described, the Avicula Seam is richly fossiliferous.

Table 3.

Ammonites

Amaltheus margaritatus

A. subnodosus

Belemnites

Lamellibranchs

Cardita multicostata	_O. inequivalvis_
Gresslya sp.	_Pleuromya sp._
Hippopodium ponderosum	_Plicatula spinosa_
Ostrea sp.	_Protocardia truncata_
Oxytoma cygnipes	_Pseudopecten equivalvis_

Gastropods

Amberlya (Encyclus) undulatus

By contrast with the _subnodosus_ shales beneath there is a preponderance of large epifaunal lamellibranchs (_Pseudopecten_, _Ostrea_, _O. cygnipes_), and deep burrowing forms (_Gresslya_, _Pleuromya_) over the more delicate thin shelled species (_Protocardia_, _Cardita_, _O. inequivalvis_). This contrast appears to represent an ecological difference and is not due entirely to the preferential preservation of stronger shells. It is probably suggestive of shallow water.

The thorough reworking of the sideritic and shaly portions of the seam ~~(plate ——)~~ by the burrows of vagile deposit eaters (pascichnia, Seilacher 1964, 298) testifies to an abundant infauna.

5. Conclusions

The Avicula Seam appears as the culmination of a cycle of deposition, which began in the subnodosus shales, and which probably resulted from the infilling of the basin of deposition. The ironstone would seem to be the shallowest unit of this cycle. The nature and abundance of the fauna and the presence of a conglomeratic and oolitic texture are compatible with this view. The facies variation within the seam is illustrated in figure 8. The question of environment will be dealt with in greater detail in the light of evidence from the other seams (page 263-305).

The thickness of the seam depends upon the depth of pre-gibbosus erosion. Two areas in which a top block of ironstone was preserved beneath the irregularities in this unconformity have been described. Of these the remnant at Grosmont provided the lowest workable ore in Cleveland. The possibility of further ore pockets, especially along the Rockcliff, Grosmont line must not be neglected. However, over most of the area the seam is of insufficient tenor to be of value.

III G I B B O S U S B E D S

The gibbosus subzone embraces the uppermost beds of the margaritatus zone from the top of the Avicula Seam to the base of the Pecten Seam. It includes two ironstone seams, the Two Foot and Raisdale Seams, which conveniently subdivide the member as follows:-

Upper gibbosus shales

Two Foot Seam

Middle gibbosus shales

Raisdale Seam

Lower gibbosus shales

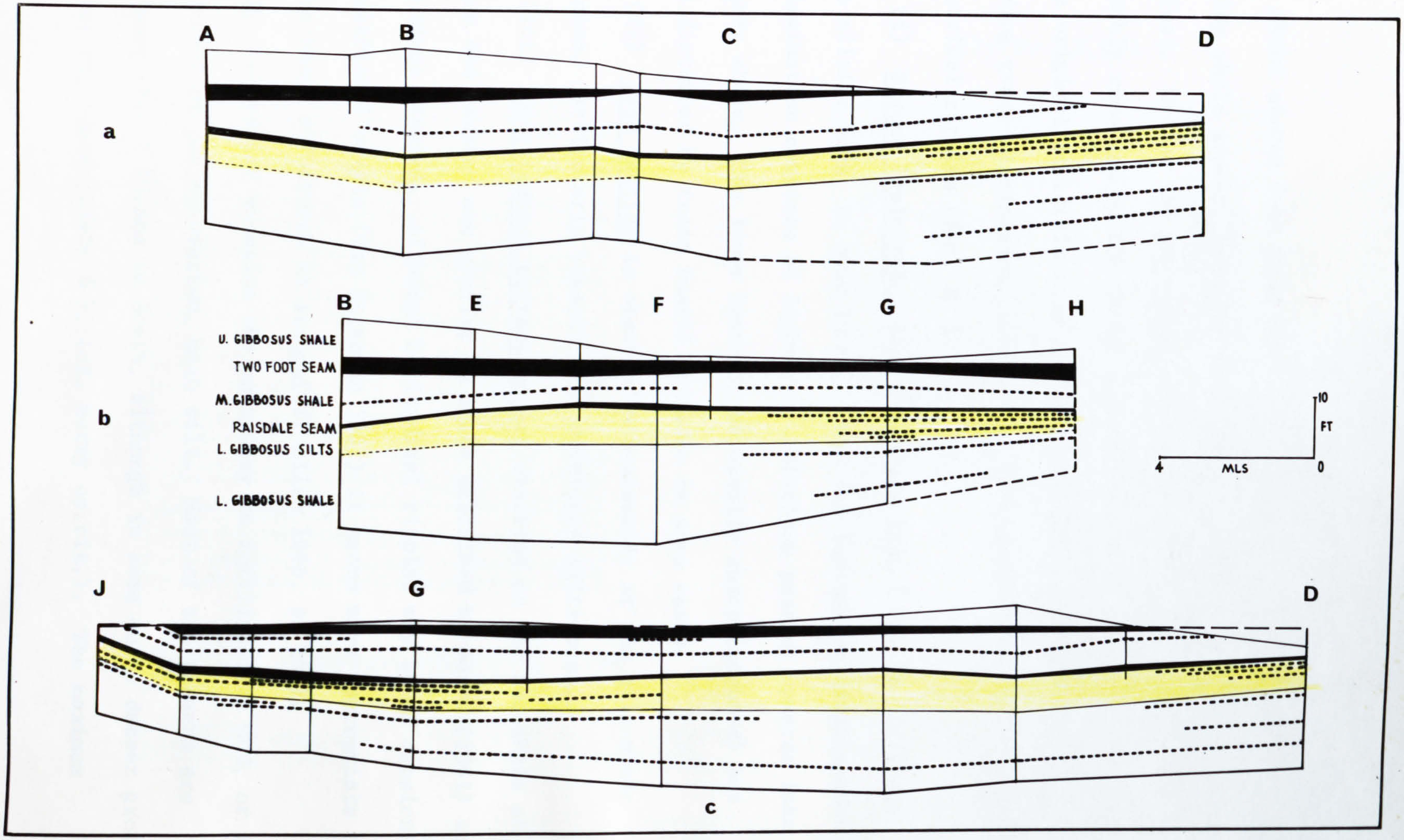
The stratigraphic details are summarised in enclosure 2 and additional information from shafts and sinkings is given in appendix ~~B~~.I

A. LOWER GIBBOSUS SHALES

1. Type Section

In Jet Wyke, Staithes, an upward passage from dark grey shale into laminated shales and siltstones, typical of these beds, is present. The sequence begins with dark grey fissile and pyritous shales with Pentacrinus ossicles. The pyrite is mainly disseminated in the organic burrows, or forms a coating on fossil wood. It also occurs in radiating veinlets (crinoid holdfasts?), which in some instances become a nucleus for carbonate deposition during diagenesis (e.g. at Hawsker). However, nodules only occur at one horizon at Staithes; bed 23 a concretionary siderite mudstone.

FIG. 10. CROSS SECTIONS OF GIBBOSUS BEDS.



About eleven feet from the base of the succession laminations of silty shale appear, becoming increasingly important in the next five feet. Unlike the subnodosus shales, these beds have not been thoroughly reworked by the fauna, and this explains the preservation of the original stratification and many delicate sedimentary structures, including graded lamination, load casts, longitudinal scour marks and assymetrical ripples (fig. 11).

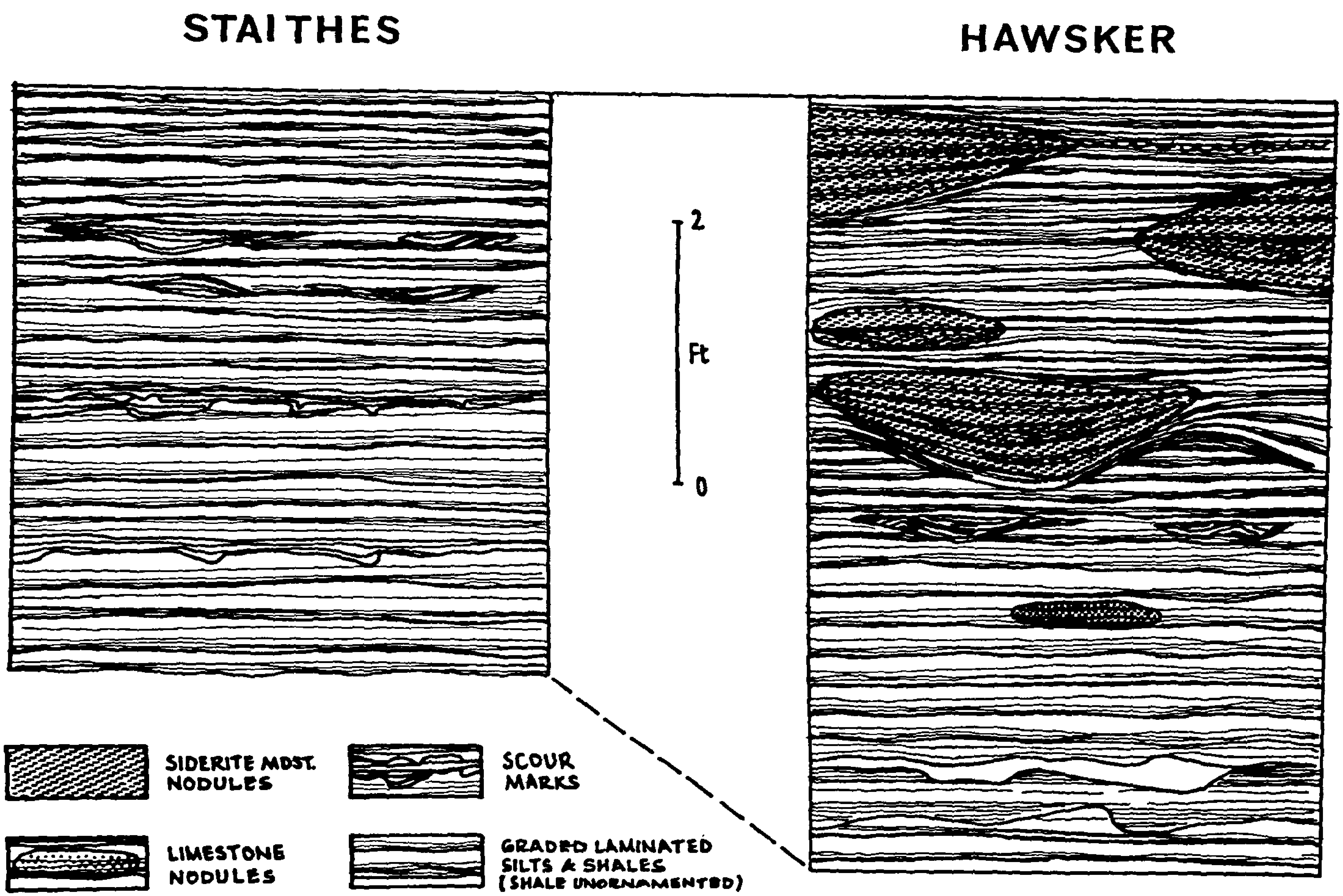
(i) Graded laminations vary from less than 1 mm. in thickness in the siltier beds, to over 10 cm. where the lamination first appears. Each lamination consists of light grey siltstone passing upwards into dark grey shale. The lower boundary is usually sharp (scoured) but may be disturbed by trace fossil activity in some cases.

(ii) Load casting is observed occasionally at the silt-shale boundaries, particularly beneath well developed siltstones.

(iii) Longitudinal current scours observed on the foreshore at Staithes and Hawsker are similar to those described by Berry (1961) as longitudinal ripples. Although longitudinal ripples may be of erosional or depositional origin (Van Straaten 1951) it seems more appropriate to describe these structures as scours(cf. Allen 1966, p. 150).

In the present examples the scours may be infilled with mud, or in the top foot of the succession, with silt. Most of the troughs are little more than 2 inches in depth, although in some cases deeper grooves and slots are found (plate 3), (cf. Berry op.cit.). The maximum

FIG. 11.



LOWER GIBBOSUS SILTS

width is about 6" and the horizontal separation from a foot to a yard. The silt filled troughs, at the top of the sequence (fig. 11) are particularly prominent, weathering proud on the foreshore as parallel ribbons, although with occasional bifurcations (cf. Berry op.cit.). Repeated scouring and sedimentation produces complex discordant horizons, which occur at intervals in the succession separated by normal graded laminated silts and shales.

The linear troughs suggest current erosion by a sediment-laden flow (Berry op.cit.) possibly analogous to that which produces sand stripes (Bagnold 1941; Stride 1963).

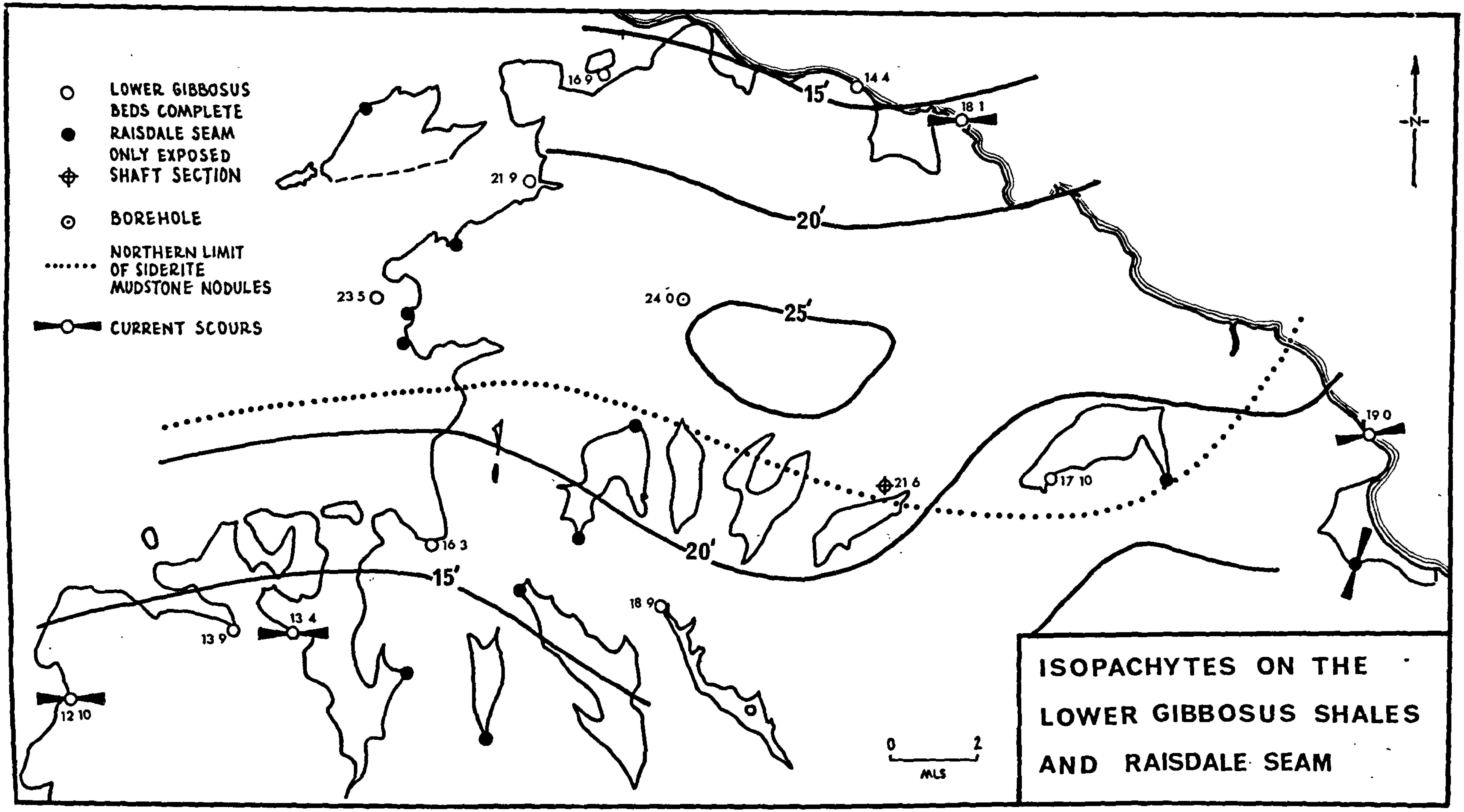
(iv) Transverse ripples occur only in the siltstones, usually restricted to the troughs of longitudinal scours. They probably formed when the silt content of the troughs rose to a critical level appropriate to the current strength.

2. Lateral variation (fig. 10).

a) Thickness

The lower *gibbosus* beds reach a maximum thickness of 23'6" in the Dimmingdale borehole (appendix I), and a maximum at outcrop of 22'1" at Cliff Rigg, seven miles due west. The north-western escarpment crosses this line at right angles, so that the succession is found to thin progressively to the north and south (fig. 10b The thinnest section lies in the extreme south west at Cod Beck, Osmotherly (11'11"). Followed west north westwards the shales thicken

FIG. 12.


ISOPACHYTES ON THE
LOWER GIBBOSUS SHALES
AND RAISDALE SEAM
LOWER GIBBOSUS BEDS COMPLETE
RAISDALE SEAM ONLY EXPOSED
SHAFT SECTION
BOREHOLE
NORTHERN LIMIT OF SIDERITE MUDSTONE NODULES
CURRENT SCOURS
N
0
2
MLS
15'
20'
25'
20'
15'
16 9
14 4
18 1
21 9
23 5
24 0
21 6
17 10
19 0
16 3
18 9
13 4
13 9
12 10

as far as Glaisdale and then thin towards Hawsker (fig. 10c). The costal section (fig. 10a) crosses the easterly extension of the Cliff Rigg-Dimmingdale line north of Whitby, but unfortunately there are no exposures until Staithes. From here the succession thins as far as Rockcliff (13'7") before a turn in the section line carries it back across the depositional strike.

b) Facies

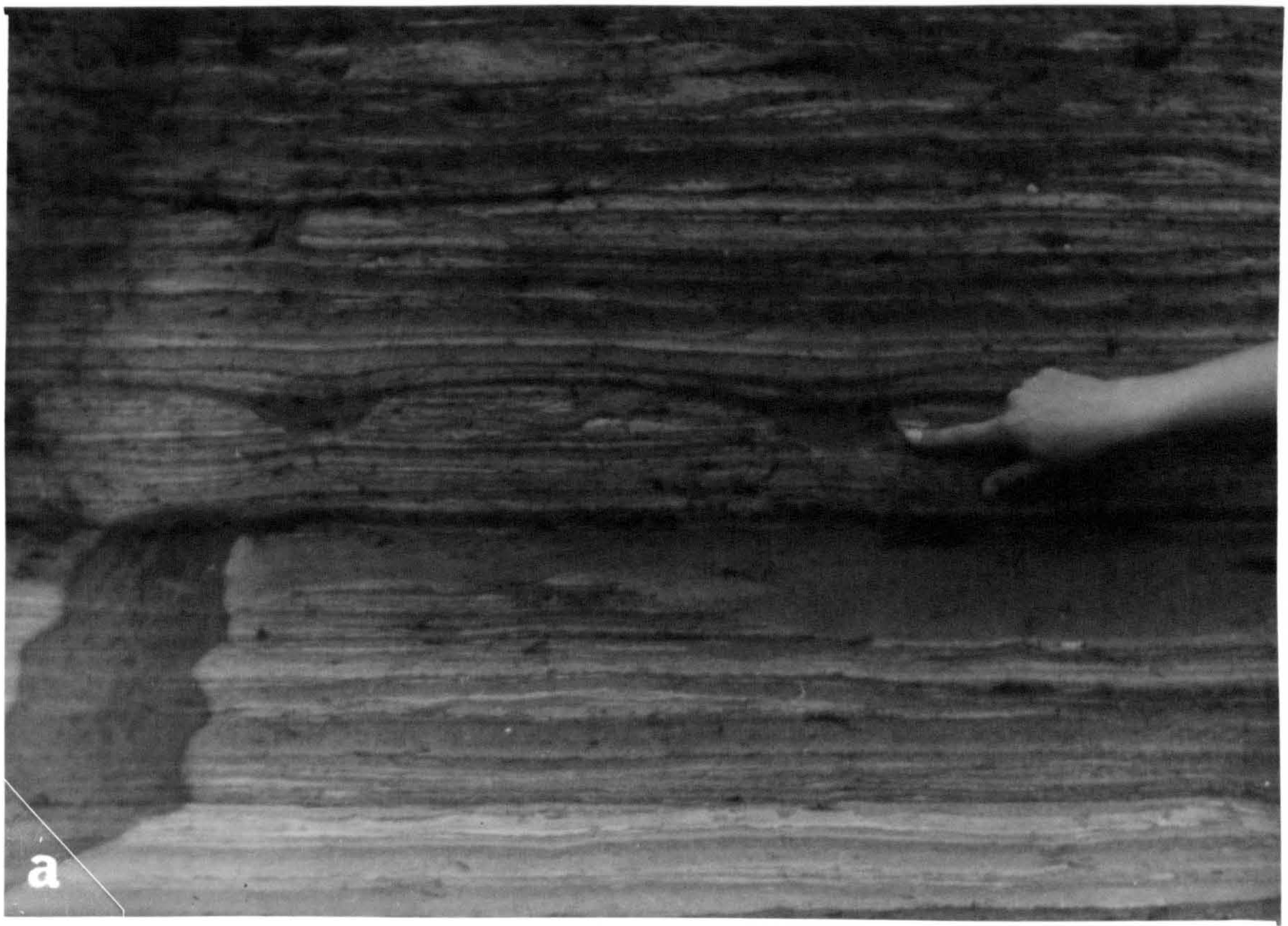
The upward passage from dark grey pyritic shales into graded laminated siltstone and shales, described from Staithes, is characteristic of these beds at all localities, although it becomes more marked in the southerly line of sections (fig. 10c) with an increasing amount of silt at the top of the sequence. Longitudinal current scours and transverse ripples can be recognised in most localities, and can be examined in detail at Hawsker (fig. 11).

The increase in silt is accompanied by a rise in iron carbonate, which has segregated into large lenticular siderite mudstone concretions. These appear in most of the southern sections, especially within the top two feet of the beds, but are entirely absent in the north.

3. Palaeontology and Palaeoecology

For the most part the lower *gibbosus* shales are only poorly fossiliferous. The nektonic species together with *Oxytoma* and *Limea* occur throughout, while *Ostrea*, *Pseudopecten* and *Protocardia* are

PLATE 3 Lower *gibbosus* siltstones: graded laminations with longitudinal current scours. Staithes



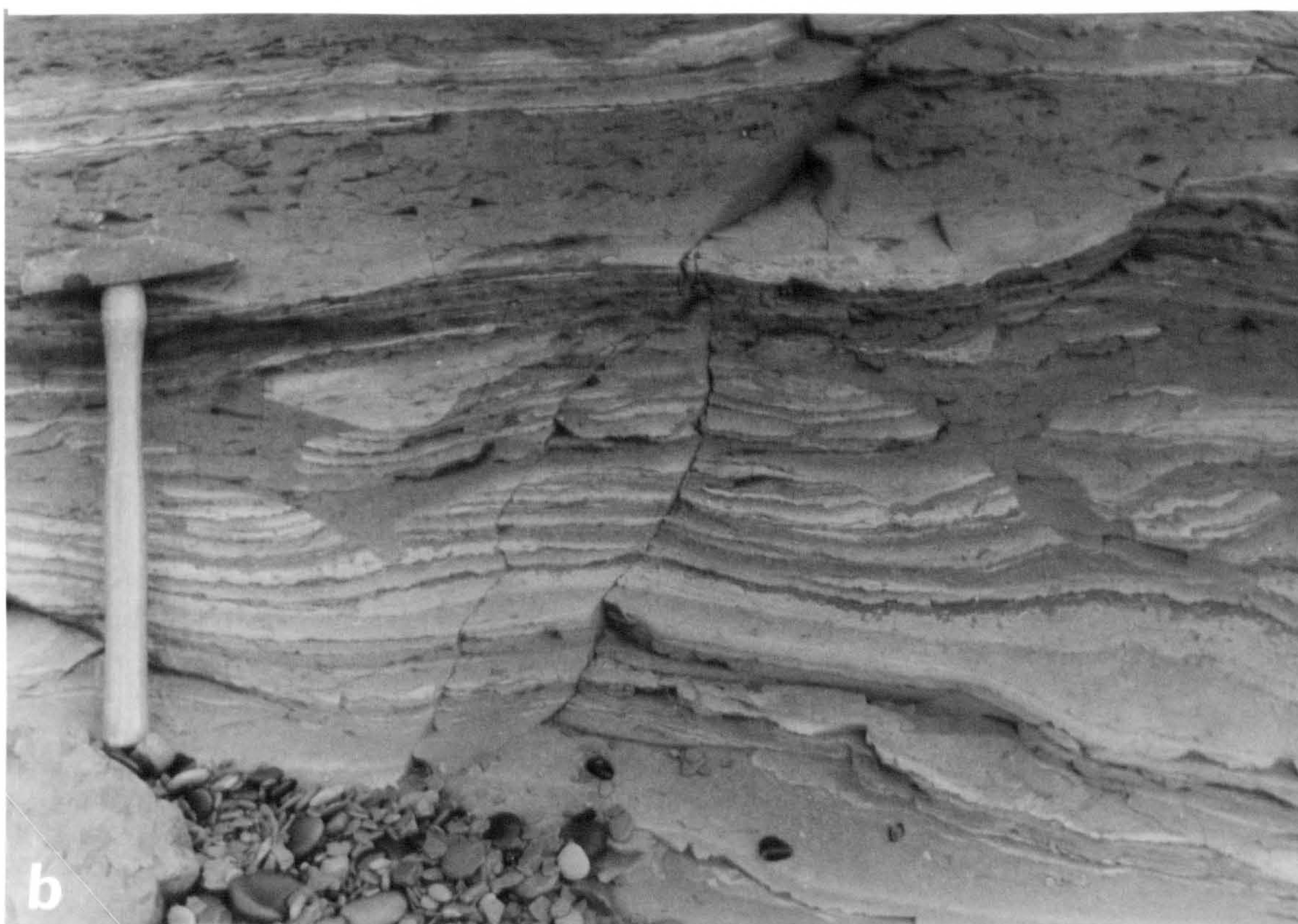


PLATE 3

Table 4

Palaeontology of the _gibbosus_ shales

Ammonites

Amaltheus margaritatus

A. gibbosus

Belemnites

Lamellibranchs

Limea acuticostata

Ostrea sp.

Oxytoma inequivalvis

Protocardia truncata

Pseudopecten equivalvis

Pentacrinus ossicles

Fossil wood occurs sporadically

restricted to the silty beds, where they occur broken and disarticulated in lenses and in the troughs of longitudinal scours. Protocardia is particularly common in the lenticular siderite mudstone nodules. Pentacrinus also occurs throughout, but is particularly abundant at the shale, silty shale junction. Significantly the infauna of these beds is very small; trace fossil activity is slight and there is a complete absence of burrowers such as Gresslya and Leda. The only infaunal species appears to be the shallow burrowing Protocardia.

4. Environment of deposition

The stratigraphic information available indicates an east-west zone of thick sedimentation which might be interpreted as a sedimentary trough or bank (fig. 12). Evidence from the middle gibbosus shales (page 44) favours the latter supposition.

At first dark grey shales were deposited upon the Avicula Seam, followed by graded laminated shales and siltstones, with an important suite of sedimentary structures.

Of particular interest is a system of longitudinal current scours, with a strong east-west preferred orientation on the coast (Staithes and Hawsker), which from the limited evidence available appears to be continued inland (see fig. 12). This trend compares closely with the trend already deduced from the isopachytes.

The nature and preservation of the sedimentary structures is indicative of rapid sedimentation, from a sediment-laden flow in a shallow (sub-littoral) environment (Moore and Scruton 1957). The faunal characteristics of the beds are consistent with this interpretation.

Both on the coast and along the western escarpment of the Cleveland Hills, the silt content in the graded laminated shales and silts increases southwards, and has affected the later diagenetic history of the beds; large lenticular siderite mudstone concretions are a feature of the southern exposures (fig. 10c). How far this reflects a southerly sediment derivation is difficult to say.

B. RAISDALE SEAM

1. Nomenclature

The name Raisdale Seam is introduced here for the first time, for a seam which lies between the Two Foot and *Avicula* Seams. It has been noted previously at several localities in the works of Tate and Blake (1876), the Geological Survey and others, but its persistence laterally has not been demonstrated before. It takes its name from its maximum development in Raisdale and at the head of Scugdale where, until now it has been confused with the Two Foot Seam (Fox-Strangways et al. 1886).

2. Recognition

Where the Seam is seen in association with the laminated silty shales of the lower *gibbosus* beds it can be identified with confidence.

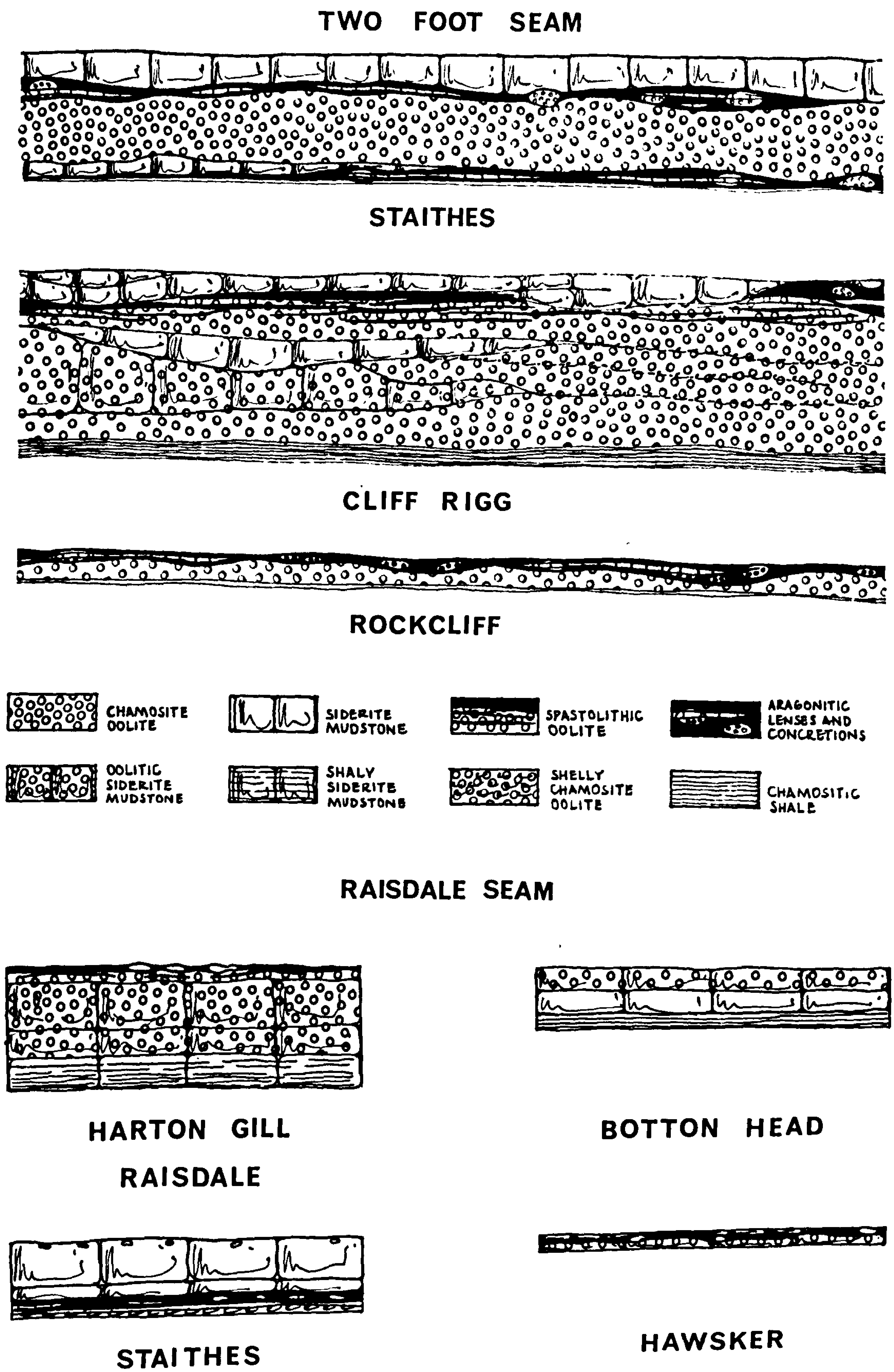

TWO FOOT SEAM
STAITHES
CLIFF RIGG
ROCKCLIFF
CHAMOSITE OOLITE
SIDERITE MUDSTONE
SPASTOLITHIC OOLITE
ARAGONITIC LENSES AND CONCRETIONS
OOLITIC SIDERITE MUDSTONE
SHALY SIDERITE MUDSTONE
SHELLY CHAMOSITE OOLITE
CHAMOSITIC SHALE
RAISDALE SEAM
HARTON GILL
RAISDALE
BOTTON HEAD
STAITHES
HAWSKER

FIG. 13.

It is distinct lithologically and faunally from all except the Two Foot Seam, with which it bears a remarkable similarity. However, in the majority of exposures the Two Foot Seam is thicker and more strongly oolitic. The lithology of the Seam is illustrated from four localities, including the Raisdale section in figure 13 , from which it may be seen that there are three main ironstone types.

(i) Winnowed green oolite, which often undergoes extreme spastolithisation during diagenesis.

(ii) Fossiliferous oolitic siderite mudstone.

(iii) Shaly siderite mudstone.

Each type passes gradationally into the others, particularly as a result of the passage of feeding burrows (<u>pascichnia</u>).

3. <u>Lateral variation</u>

From the sections (encl. 2) it can be seen that the Raisdale Seam is developed at a maximum in the north and west of the area. However, the thickness varies rather erratically. This variation is probably only in part original, some resulting through differential compaction, and siderite mudstone segregation during diagenesis. The Seam reaches its maximum development in the most westerly exposures (Scugdale 1'6", Raisdale 1'4", Eston 1'3"), where it consists in the main of strongly oolitic shelly siderite mudstone. Eastwards in the Blackmoor sections this appears to pass laterally into a thin shaly siderite mudstone. South east of Eston the deterioration is somewhat irregular, but the

Seam consists of two parts:-

(ii)	oolitic siderite mudstone	4" - 6"
(i)	shelly spastolithic oolite	2" - 4"

the total thickness being dependent upon the development of siderite mudstone. Thus at Staithes and Rockcliff the Seam is 9-10" thick, comprising 6" siderite mudstone, while at Waterfall Beck, and Hawsker Bottoms it is 2-3" thick and largely comprised of spastolithic oolite.

4. Palaeontology and Palaeoecology

The fauna of this Seam consists mainly of nektonic forms (abundant belemnites), epifaunal species (O. inequivalvis, L. acuticostata, P. equivalvis) and shallow infaunal types (abundant P. truncata). Deep burrowing forms are rare. Large shells are also rare; both P. truncata and P. equivalvis are smallforms. Finally the fauna has been subjected to a large degree of disarticulation and comminution (Table 5).

The conditions necessary for the preservation of this kind of assemblage would be satisfied on a shifting bottom with moderate currents, sufficient to cause breakage amongst the larger shells lying on the surface, but insufficient to uncover and remove smalllfragments preferentially buried within the sediment. The abundance of belemnites indicate that the deposit is condensed.

5. Conclusions

Like the *Avicula* Seam this bed occurs at the culmination of a cycle of deposition indicative of shallowing water, and it is clear that it represents an important break in the *gibbosus* subzone, and in the evolution of the basin of deposition. However, the Raisdale Seam rests with apparent conformity upon the shales beneath, although a hiatus at the base of the Seam is indicated by a belemnite shell bed in many localities.

Neither the thickness nor the lithology appear to be influenced by the beds below; they vary rather eratically over short distances and yet this remains one of the most persistent ironstone horizons.

C. MIDDLE GIBBOSUS SHALES

In the type section the shales between the Raisdale and Two Foot Seams are dark grey, fissile and pyritic, similar to those at the base of the *gibbosus* beds. Occasional silt lenses occur but the silt content is low by comparison with the *subnodosus*, *apyrenum* and *hawskerense* shales. This probably explains their greater fissility. The only discernable facies variation over the area as a whole is diagenetic, although it probably reflects an original depositional variation. In the vicinity of Eston there are no concretions, but further south feeble argillaceous siderite mudstone nodules occur near the middle of the sequence (e.g. Staithes), increasing in size to the south until a second nodule horizon appears in the south-westerly exposures (fig. 14). This parallels the development of siderite mudstone concretions in the lower gibbosus shales (page 37).

The most important feature of this division is its antipathetic relationship with the lower gibbosus shales at many localities (fig. 12). The middle gibbosus shales reach their maximum at Rockcliff (10'4") where the lower gibbosus shales are at a minimum, and their minimum at Hutton Lawcross (4'7") and Cliff Rigg (5'3") where the beds below are known at a maximum. The evidence from the Dimmingdale borehole also appears to be in agreement. The most feasible explanation of this relationship lies in the presence of a residual bottom relief from the lower gibbosus beds. Apparently this relief played little part in the deposition of the Raisdale Seam.

The fauna of these beds is sparse, restricted to nektonic ammonites and belemnites and vagile epifaunal types (O. inequivalvis, P. equivalvis) (see Table 4).

D. TWO FOOT SEAM

1. Nomenclature

The name Two Foot Seam was introduced by Marley (1857 p. 189) in the mines at Eston, and is derived from the average thickness of the bed on the northern escarpment (Anderson 1942). Subsequently the lateral persistence of this ironstone along the coast was shown by Tate and Blake (1876 opposite p. 124), who adopted the name Bottom Seam and correlated it with the Bottom Seam of Grosmont (i.e. the *Avicula* Seam). However, Barrow (1880) restored the earlier name and drew attention to the true stratigraphic relationship between the Two Foot and *Avicula* Seams, on the northern escarpment, on the coast and in Eskdale (see Fox-Strangways 1892).

2. Recognition

In the past there has been a great deal of confusion in the identification of the Two Foot Seam; it has been confused with the *Avicula* and Raisdale Seams and mistaken for the *Pecten* Seam (Anderson 1942, p. 6) and for the Main Seam, Bottom Block. Particular care must be taken in distinguishing it on the southern margins of the area because:-

(i) in the south-west the attenuation of the *spinatum* beds brings the Main, *Pecten* and Two Foot Seams into close proximity, so that they appear as one seam (Raisdale and Scugdale, see appendix I).

(ii) in three localities the ironstone is known to have been removed by erosion (page 50) so that the Raisdale Seam becomes the highest seam in the *margaritatus* zone (Hawsker, Howdale Gill and Cod Beck, see appendix I).

The lithology and thickness of the seam is illustrated in three characteristic localities (fig. 13), which show the following ironstone types.

(i) spastolithic green oolite 'roe stone'

(ii) fossiliferous oolitic siderite mudstone

(iii) siderite mudstone

(iv) chamositic sideritic shale

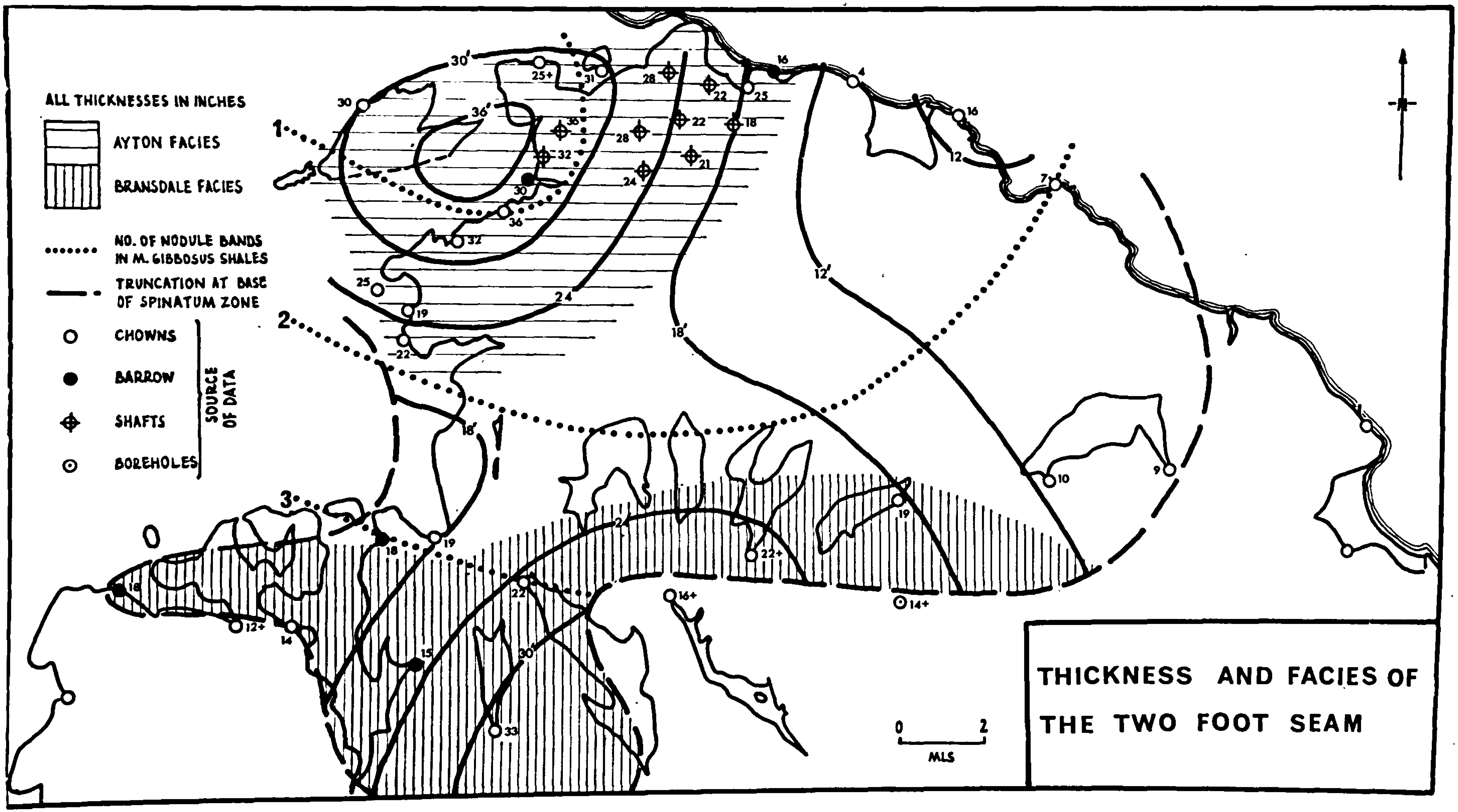
3. Lateral variation

The Two Foot Seam and to a lesser extent the Raisdale Seam are remarkably uniform in lithology and thickness over very large areas. Although the former varies in thickness from 4 inches to 3 feet, the lithological association of siderite mudstone and chamosite oolite remains the same over at least 400 square miles. Figure 14 illustrates isopachytes for the seam, and shows the areas in which the original thickness was reduced by post gibbosus erosion, (see page 50). Two 'highs' stand out, one on the northern escarpment, and the other in the dales of Blackmoor, separating two areas of thinner sedimentation on the western escarpment and in the lower reaches of the River Esk.

a) Northern escarpment

The stratigraphic details of this seam are well known on the northern escarpment from outcrop and underground sections, the ironstone comprising wedges of shelly oolitic siderite mudstone and chamosite oolite (see fig. 13) said to reach a maximum thickness of about 3 feet at Skelton Park Mine (Anderson 1942, p. 7). The 'roe'stone, a beautiful, clean-washed chamosite oolite, very susceptible to spastolithisation

FIG. 14.


ALL THICKNESSES IN INCHES
AYTON FACIES
BRANSDALE FACIES
NO. OF NODULE BANDS IN M. GIBBOSUS SHALES
TRUNCATION AT BASE OF SPINATUM ZONE
CHOWNS
BARROW
SHAFTS
BOREHOLES
SOURCE OF DATA
0
2
MLS
THICKNESS AND FACIES OF THE TWO FOOT SEAM

during compaction, is characteristic of the Two Foot Seam in this area.

b) Blackmoor and the south-west

Although in places the upper part of the seam has undergone denudation (fig. 14) it is clear that a second 'high' exists in this area, centred on Bransdale, where a thickness of 2'9" was recorded. How far south this thickening continue is impossible to say. Once again the seam is built of wedging sideritic oolites; more shelly in this case than on the northern escarpment. The seam continues thus westwards into Scugdale and as far east as Glaisdale.

c) Lower Eskdale and the coast

East of a line drawn between Glaisdale and Skinningrove (18 inch isopachyte) the character of the bed changes. The wedges of sideritic oolite disappear leaving thin siderite mudstones and 'roe' stone horizons (Rockcliff 4", Kettleness 7"). It is clear that this change is responsible for the decrease in thickness.

4. Palaeontology and Palaeoecology

The Two Foot Seam is abundantly fossiliferous but particularly rich in epifaunal lamellibranchs (E. lunularis, L. acuticostata, O. inequivalvis) and thin walled aragonite shells, typical of shallow infaunal genera (Astarte, Cardinia, Cardita, Protocardia and many others not identified). The greater part of this fauna is disarticulated, comminuted and often well rounded indicating considerable reworking.

Infaunal genera (*Gresslya* and *Pleuromya*) are rather rare and are restricted to wackestone-mudstone facies.

Belemnites are abundant and ammonites more common than in the surrounding sediments, indicating condensation.

5. Conclusions

The Two Foot Seam closely resembles the Raisdale Seam in lithology, palaeontology and lateral persistence, and care is needed in distinguishing the two in unfavourable exposures. However, it is slightly thicker on average, and somewhat more oolitic. Unlike the Raisdale and *Avicula* Seams it does not appear as the culmination of a sedimentary cycle beginning in the beds beneath, but comes as a surprising interruption to a sequence of fine grained shales. However, the base of the seam marks an important hiatus with a belemnite-shell bed containing occasional siltstone pebbles which may indicate a former siltstone phase at the top of the middle *gibbosus* shales. Part of the thickness variation noted in these beds (page 44) might be ascribed to erosion prior to the deposition of the Two Foot Seam but detailed evidence for an angular disconformity such as that beneath the *Avicula* Seam (pages 23-24) is lacking.

Fauna, wedge cross bedding, and oolitic texture all favour deposition in shallow water.

Table 5.

Palaeontology of the *gibbosus* ironstones

Ammonites

Amaltheus margaritatus

A. gibbosus

Belemnites

Lamellibranchs

Astarte sp.	*Ostrea sp.*
Cardinia sp.	*Oxytoma inequivalvis*
Cardita multicostata	*O. cygnipes*
Entolium lunularis	*Pleuromya sp.*
Gresslya sp.	*Protocardia truncata*
Limea acuticostata	*Pseudopecten equivalvis*

Gastropods

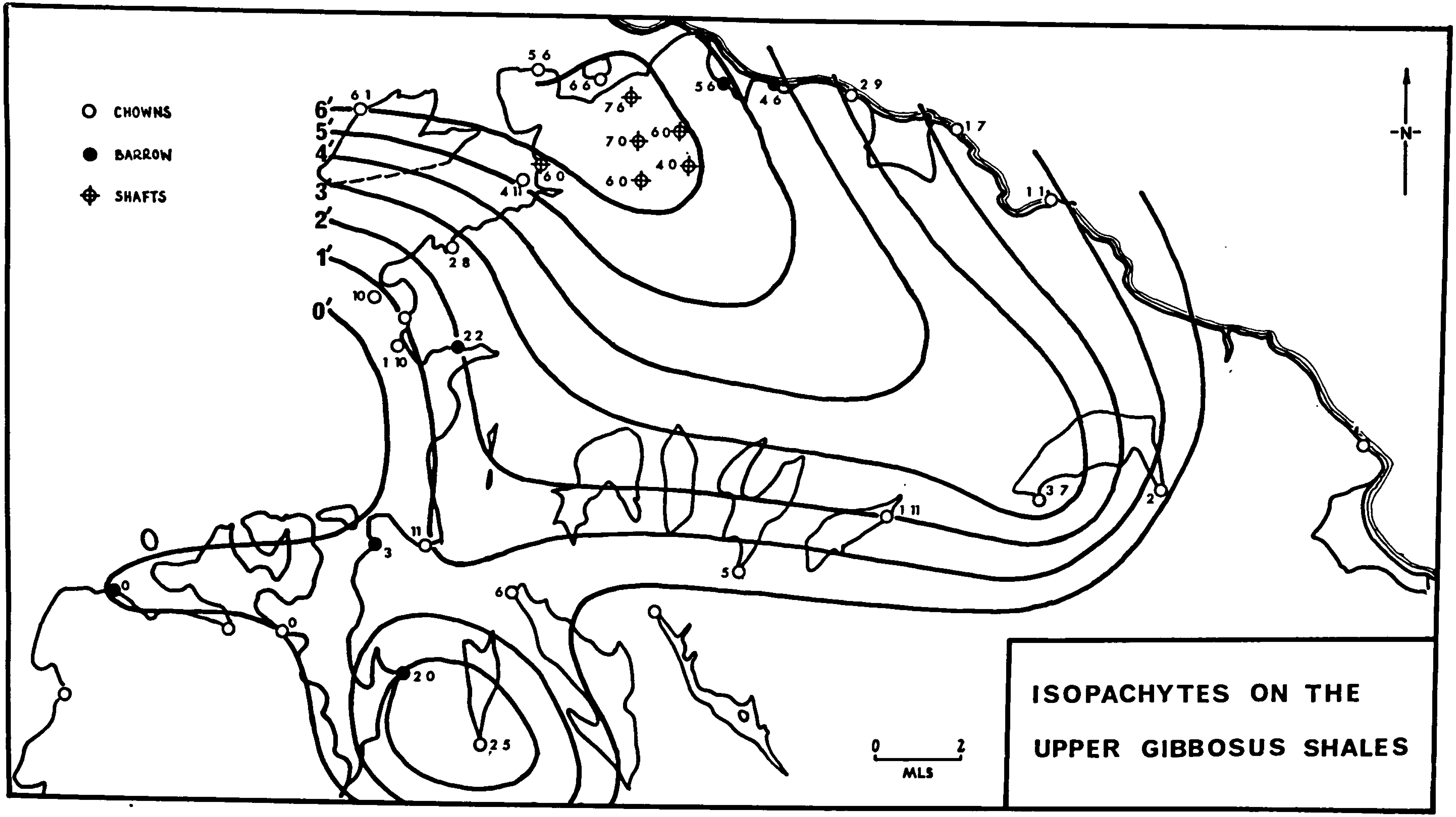
Brachiopods

* *Lobothyris* sp.

Ostracods and Foraminifera

Wood

FIG. 15.



ISOPACHYTES ON THE UPPER GIBBOSUS SHALES

E. THE UPPER GIBBOSUS SHALES

At Staithes 1'7" of dark grey fissile and pyritic shale, identical lithologically and faunally with the middle gibbosus shales, Table 4, intervenes between the Two Foot Seam and the base of the Pecten Seam, which also marks the base of the spinatum zone.

From an examination of the section lines (fig. 10) it is clear that the base of the Pecten Seam is highly transgressive, so that the thickness of these shales depends upon the depth of margaritatus/spinatum erosion. In most localities only the upper gibbosus shales are truncated but in some areas erosion reaches the Two Foot Seam and the beds below (fig. 15).

The nature of the unconformity is illustrated by the isopachytes drawn on the upper gibbosus shales. Downcutting was greatest in the south-west and south-east so that the highest beds in the margaritatus zone are preserved in the north, at Eston. The thickening in the vicinity of Bransdale presents the only irregularity in this picture but it makes extrapolation south of the present area uncertain.
The changes in the configuration of the basin of deposition and of the local palaeogeography, which this period of denudation brought about were fundamental in the evolution of the environment for the development of the workable ironstones of the spinatum zone.

IV APYRENUM BEDS

The *apyrenum* subzone is the lower palaeontological subdivision of the *spinatum* zone, comprising the strata from the base of the *Pecten* Seam to the top of the Main Seam, a thickness of between 2'2" and 18'11", of chamositic and sideritic ironstones, and shales. The succession may be stated as follows:-

(iii) Main Seam - chamosite oolites, siderite mudstones and shale equivalents.

(ii) Black Hard - shale.

(i) *Pecten* Seam - siderite and chamosite mudstones, and shale equivalents.

The natural exposures of these beds have been supplemented by a large number of artificial exposures opened during the working of the ironstone from outcrop, and by a great deal of underground information from borings and sinkings. Most of the latter has been summarised by the Geological Survey, (Lamplugh et al. 1920, Whitehead et al. 1952). The stratigraphic information gathered during the present work is given in enclosure 3 .

The whole of the *apyrenum* subzone may be examined at beach level at the type locality, Brackenberry Wyke, Staithes. The Main Seam was obtained from the scars and from the cliffs, in the Port Mulgrave or Rosedale mine and the collapsed pillars and bords of these workings are now being attacked by the sea especially at Old Nab.

A. PECTEN SEAM

1. Nomenclature

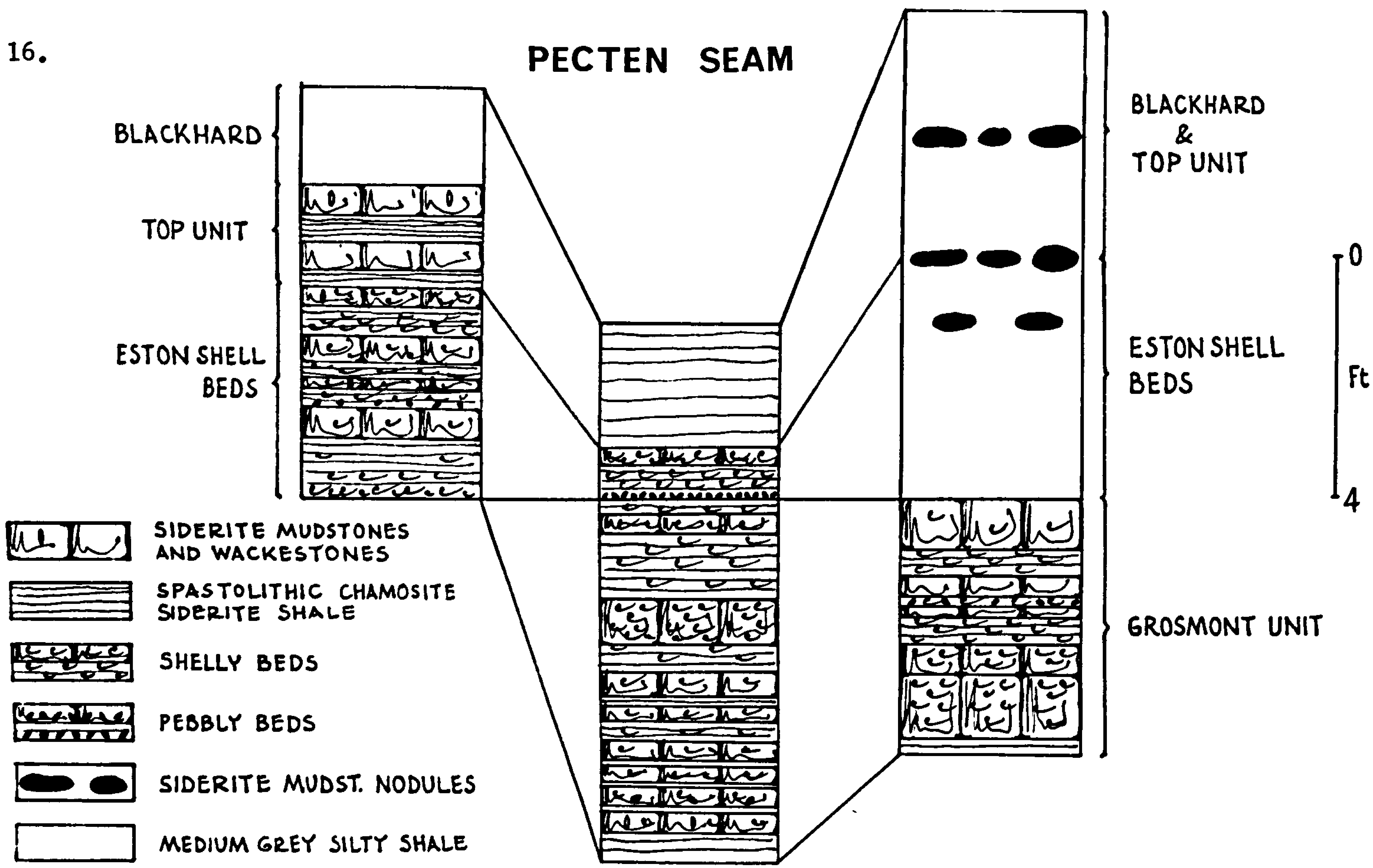
The name Pecten Seam was first introduced in the Grosmont mines for an ironstone at first believed to be the equivalent of the Main Seam, Top Block of North Cleveland (Marley 1857, p. 179) but later shown to lie beneath the Main Seam (Barrow 1888, p. 18). The name derives from the prominence of *Pseudopecten equivalvis*.

2. Recognition

The recognition of the true stratigraphic position of the Pecten Seam by Barrow (loc. cit.) marked a major step forward in the interpretation of the Cleveland Ironstone Formation. In particular it was the fossiliferous nature and distinctive lithology of the seam which enabled him to separate it from the Main Seam. These remain the best criteria for its identification. Barrow comments on the difficulty of ascribing limits to the seam and hence of making bed for bed correlations between sections (1888, p. 19). However, although the stratigraphy is complicated by lateral facies changes and an angular disconformity, the following subdivisions can be made.

The thickness and lithology of these units is illustrated from three localities, Staithes, Hutton Lowcross and Grosmont in figure 16 .

FIG. 16.


PECTEN SEAM
BLACKHARD
TOP UNIT
ESTON SHELL BEDS
BLACKHARD & TOP UNIT
ESTON SHELL BEDS
GROSMONT UNIT
0
Ft
4
SIDERITE MUDSTONES AND WACKESTONES
SPASTOLITHIC CHAMOSITE SIDERITE SHALE
SHELLY BEDS
PEBBLY BEDS
SIDERITE MUDST. NODULES
MEDIUM GREY SILTY SHALE

UPPER PECTEN SEAM

(iii) Top Unit

Two or three beds of siderite mudstone with intervening sideritic, chamositic shales. Rather unfossiliferous (No ammonites). Passes laterally into shale.

(ii) Eston Shell Beds

Shelly siderite and chamosite mudstone and shales. Very fossiliferous:- *Pseudopecten equivalvis* (J.Sow.); *Liostrea sp.*; *Plicatula spinosa* (J.Sow.); *Oxytoma cygnipes* (J.Sow); *O. inequivalvis* (J.Sow.); *Pholadomya* sp.; *Pleuromya* sp.; *Gresslya* sp.; *Cryptaenia* sp.; *Tetrarhynchia tetrahedra* (J.Sow.); *Homeorhynchia capitulata* (Tate); *Lobothyris punctata* (J.Sow.); *Aulacothyris resupinata* (J.Sow.); belemnites, etc. but no ammonites. Passes laterally into shale. (Note the majority of Ager's (1956) brachiopods from the Yorkshire province were probably derived from these beds).

LOWER PECTEN SEAM

(i) Grosmont Pecten Unit

Fossiliferous siderite mudstones and sideritic chamositic shales similar to above but separated by a minor disconformity. (*Pleuroceras apyrenum* (S.Buckman); *P. solare* (Phillips); *A. margaritatus* de Mont.; *Pseudopecten equivalvis* (J.Sow.); *Liostrea* sp.; *Plicatula spinosa* (J.Sow.); *Oxytoma cygnipes* (J.Sow.); *O. inequivalvis* (J.Sow.); *Pseudolimea acuticostata* (Münst); *Pleuromya* sp.; *Gresslya* sp.; *Arcomya* sp.; *Cardinia* sp.; *Hippopodium ponderosum* J.Sow.; *Tetrarhynchia tetrahedra* (J.Sow.); belemnites, etc.)

3. Lateral variation

The variation within these beds can be explained in terms of the relative facies and thickness of each unit. These complicate Barrow's conception of the seam (op. cit.) but do not fundamentally alter his explanation of the changes which lead to the Pecten Seam being united with the Main Seam at Eston. The present interpretation of the stratigraphy is shown in figure 17.

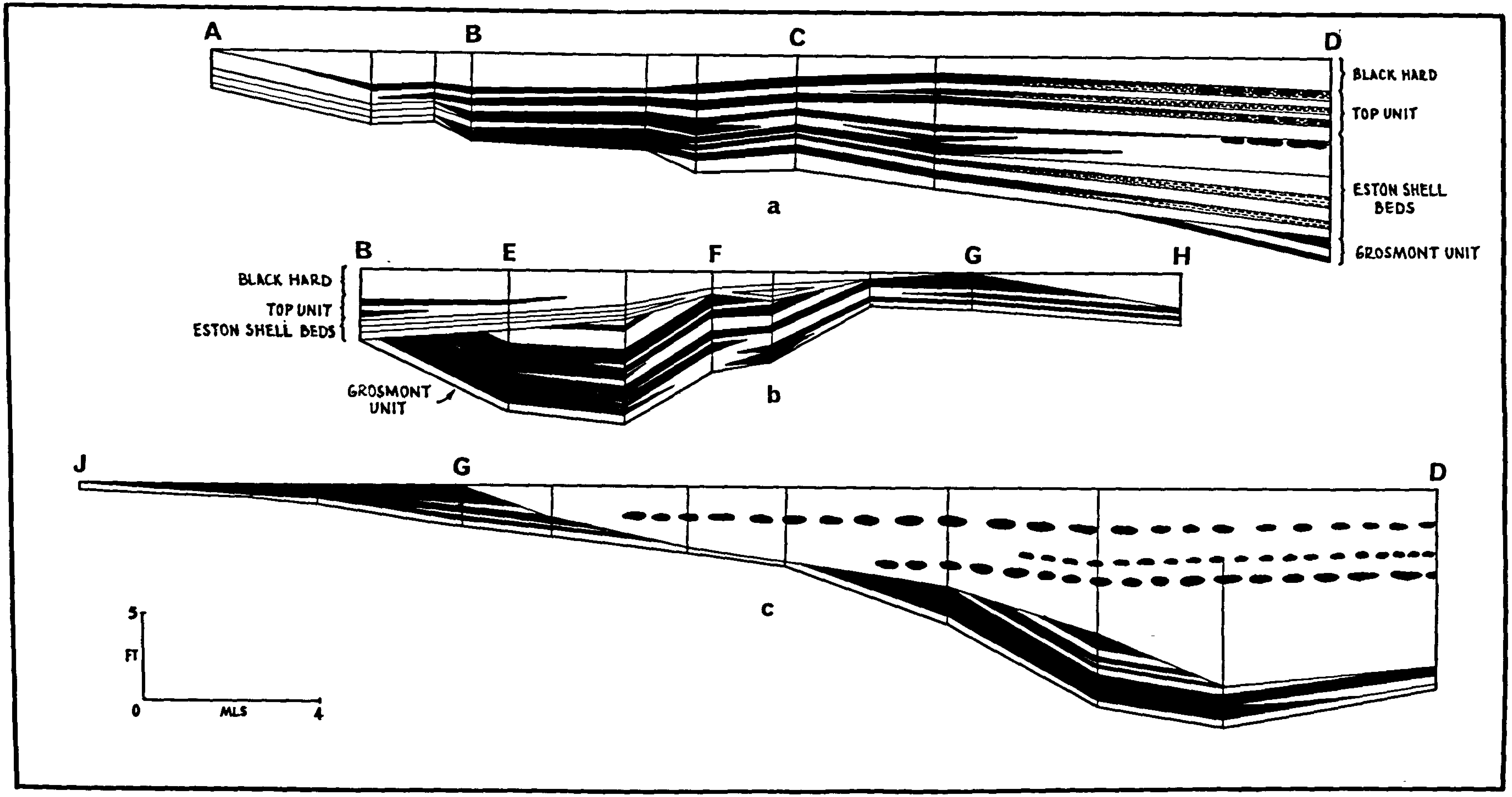
(a) The Grosmont Pecten Unit

The bottom unit of the seam is more limited in extent than the units above. It is entirely absent from the exposures between Eston and Kettleness (fig. 17a) but appears on the coast at Hawsker and may be followed to Howdale Gill, Iburndale and Grosmont where it reaches a thickness of 4'2" before thinning again through Blackmoor (fig. 17c). However, the unit reaches its maximum thickness of 5'11" at Hutton Lowcross. In every locality it comprises shelly oolitic siderite mudstones and shelly chamositic-sideritic mudstones and shales; unlike the higher units there is no lateral facies change. The thickness of the Grosmont Pecten Unit varies depending upon the depth of erosion beneath the Eston Shell Beds.

(b) The Eston Shell Beds

The "Cockle Bed" of Tate and Blake (1876, p. 120) and the fossiliferous part of Barrow's "shelly bed" at Eston (1888, p. 29), belong to the middle unit of the Pecten Seam, here called the Eston Shell Beds, which overstep the Grosmont Pecten Unit. The nature of

FIG. 17. CROSS SECTIONS OF THE PECTEN SEAM



this overstep is seen on the northern escarpment, where within a few miles, between Eston and Hutton Lowcross, and between Skelton Beck and Waterfall Beck, the pebbly base of the Eston Shell Beds transgresses over the Grosmont Pecten unit on to the ~~lower~~ gibbosus shales (fig. 17b). In this vicinity the middle unit consists of shelly chamosite mudstone; 1'1" thick at Eston. Towards the coast it thickens and the chamosite mudstones give way to shelly siderite mudstones, which comprise the bulk of the seam at Rockcliff, Grinkle, Staithes and Kettleness. However, at the last locality the unit has begun to deteriorate, so that where it is next exposed at Hawsker and Grosmont, it has passed into alternations of shale and sideritic shale with siderite mudstone nodules.

(c) Top Unit

In the exposures at Eston Mines, the Eston Shell Beds pass upwards into a dark green spastolithic chamosite mudstone differing only in being much less fossiliferous. Apparently this mudstone was sufficiently ferruginous to be worked with the Main Seam above. Barrow describes the splitting of the mudstone by shale in the main roadway which passes under Eston Hill to Chaloner's Pit (1888, p. 24) and in the exposure at Scugdale, which is now lost, he measured the following (1888, p. 22):-

5.	Base of Main Seam, looks like a red gravel -	
4.	Mottled Shale, with streaks of ironstone (Blue Mottle)	1' 0"
3.	Shales, crumbles to Pieces (Black Hard)	2' 0"
2.	Shelly beds, with ironstone and shale partings Pecten Seam (Top Unit and Eston Shell Beds)	2' 4"
1.	Ferruginous shale (Upper gibbosus shale)	5' 8"

The definition of the terms 'Blue Mottle' and 'Black Hard' will be discussed later. In this work the base of the Main Seam has been taken at the base of bed 4, and the top of the Pecten Seam at the top of bed 2, although it is clear that the Blue Mottle, Black Hard and Top Unit, Pecten Seam belong to the same lithological and faunal facies.

The Top Unit undergoes the same kind of facies change as the Eston Shell Beds. From a chamosite mudstone at Eston thin siderite mudstones appear at Court Green (Barrow 1888, p. 21), Waterfall Beck, and Upleatham, and gradually become more prominent towards the coast. They are separated by sideritic shales, also developed at the expense of the chamositic mudstone. Between Kettleness and Hawsker and Kettleness and Grosmont the siderite mudstones pass into sideritic shales with siderite mudstone nodules.

4. Palaeontology and Palaeoecology

The Pecten Seam embraces the most fossiliferous strata in the Ironstone Formation, with a fauna rich in both individuals and species (see page 53). Once again this list may be broken down into its ecological components.

(i) The Nekton:- ammonites and belemnites.

(ii) The Epifauna:- besides the usual assemblage of epifaunal lamellibranchs (Pseudopecten, Oxytoma, Liostrea, Plicatula) the seam contains an important group of terabratuloid and rhynchonelloid brachiopods which may have lived epiphytically on seaweeds (Ager 1962).

(iii) The Infauna:- a large number of genera are demonstrably infaunal, being preserved in their positions of life. These include Ancomya, Pleuromya and Gresslya. Pascichnia and Repichnia including the ichnogenus Rhizocorallium are also common.

Each unit of the seam is characterised by a slightly different facies fauna. In the Grosmont Pecten unit the burrowing lamellibranchs are more important than in the other units, while brachiopods are most abundant in the Eston Shell Beds. By contrast the Top Unit is much less fossiliferous.

The dearth of ammonites in the upper units was pointed out by Howarth (1955, p. 156, 157): Pleuroceras has been recorded at only one locality in strata attributed to the Eston Shell Beds (Tate and Blake 1876, p. 148). The Grosmont Pecten unit on the other hand yields Pleuroceras fairly commonly on the northern escarpment and at Hawsker.

5. Conclusions

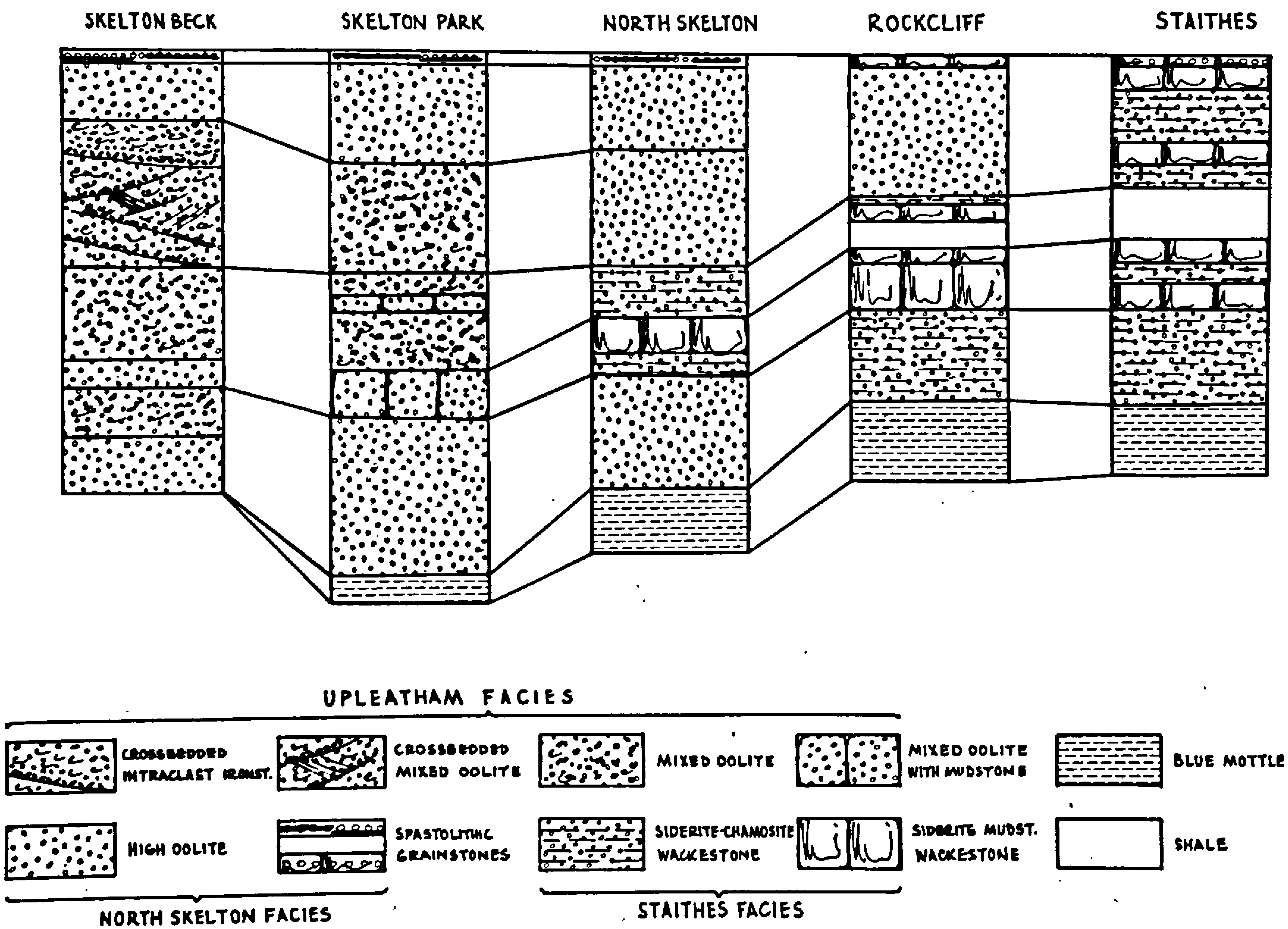
Of all the ironstone seams the Pecten Seam is one of the most distinctive because of its fauna and the characteristic alternation between siderite mudstones and chamositic shales, which prevails in all the sections where ironstone is developed. However, despite the apparent similarity between the different units which make up the seam, an important break occurs between the lowermost unit, the Grosmont Pecten unit, and the upper units, in the form of an angular disconformity. Most significantly while ammonites occur in the Lower Pecten Seam they are almost completely absent from the upper, the Grosmont Pecten unit, being the highest horizon at which P. solare occurs. Since the apyrenum subzone is defined by the range of P. solare this disconformity may well form the apyrenum-hawskerense boundary. Some adjustment to the subzonal scheme in Yorkshire is therefore necessary to bring correlation in line with southern England and the Midlands. However, for the present Howarth's original (1955) divisions are retained (see also pages 83-85).

B. MAIN SEAM

1. Nomenclature

In writing of the Middle and Upper Lias at Rockcliff and Boulby, Hunton(1836) described the "Main Ironstone bands", as comprising "connected blocks of hard ironstone a foot and upwards in thickness with thin seams of shale intervening, 25 feet." This division obviously includes both the Pecten and the Main Seam of the present nomenclature together with about ten feet belonging to the hawskerense beds. The measurement is later cited by Marley (1857, p. 178) and attributed to "the main bed of ironstone." However, Marley uses Main Seam rather loosely in reference not only to the spinatum ironstones as a whole but also for the workable part of the succession above (conterminous with the present Main Seam). It was in this restricted sense that Tate and Blake (1876, p. 119) and Barrow (1888, p. 24) used the name, to be followed by all subsequent authors. In addition a useful terminology has grown up amongst the mining fraternity and has been incorporated within the literature. The definition given to the Main Seam in this work agrees closely with that of previous authors and is illustrated with reference to figure 18 .

FIG. 18. CLEVELAND MAIN SEAM.



at different localities. In the Upleatham Mines, according to Tate and Blake (1876, p. 119) the term 'Black Hard' was used to describe the inferior ironstone between the oolitic portion of the Main Seam and the Eston Shell Beds, a "compact splintery stone dark-green in colour, like a hard mudstone, perfectly devoid of oolitic structure, which prevails in all the lighter parts of the seam." Passing southwards this "Green stone" (Hallimond 1925, p. 47) splits into two parts, a chamositic siderite mudstone above and a shale below which is responsible for the separation of Main Seam from the Pecten Seam as recognised by Barrow (1888, p. 24). The usual practice in the Skelton royalties appears to have been to refer to the upper layer as the 'Blue Mottle' because of the abundance of Rhizocorallium burrows, and the lower as the 'Black Hard' shale; it is therefore in this sense that the two terms have been used during the present work.

Although following weathering at outcrop each of these units is fairly clearly defined, in the fresh rock underground the divisions are much more difficult to locate and the usual practice in the southerly group of mines was to refer all the strata between the workable base of the Main Seam and the Pecten Seam as 'Black Hard' (see for example Dunham in Whitehead et al. 1952, p. 47). From mining records it seems that working was usually discontinued within the 'Blue Mottle', although more was taken in the north and east than in the south and west. In consequence records of the base of the Main Seam are difficult to evaluate, and the isopachytes given in figure 20 have been calculated by averaging all the available data from the literature. What these isopachytes really represent is the average thickness of workable ironstone including the Middle Band, but where possible the total thickness of the Main Seam and that part assigned to the Blue Mottle are given for comparison.

3. Lateral variations

The gradual deterioration of the Main Seam in a southerly direction has been brought out in the works of Tate and Blake (1876, p. 121-4) and Barrow (1888, p. 24-25). It is an expression of the seam's variation in thickness and facies.

a) Thickness

The overall thickness of the Main Seam and its shale equivalents is illustrated in figures 18 and 19, and isopachytes are provided within the area of the northern ore field. From a minimum observed thickness of 1'10" at Cod Beck, Osmotherley, the stratum thickens continuously north-north eastwards up to a maximum of about 11 feet at Eston. This feature is illustrated by the exposures on the western escarpment (fig. 19b) and borne out by an interpretation of the Blackmoor sections (fig. 19c). The only reversals in this trend occur in the vicinity of Bransdale, and in the north around Brotton where the wasting of the seam (Tate and Blake 1876; Barrow 1888, p. 26) places a northern limit to the thickening. Thus the line of section between Eston and Hawsker (fig. 18a) lies along the zone of greatest thickness. Assuming that the Main Seam is an isochronous unit, the question now arises as to how far the isopachytes represent the original depositional thickness, and to what extent this was modified by subsequent penecontemporaneous erosion. Although the seam is overlain non-sequentially by beds of the hawskerense subzone and local reworking appears to have taken place, there is no evidence to indicate substantial truncation at the top of the seam; the characteristic spastolithic horizon (T 0) persists even after the seam is overstepped (see fig. 19).

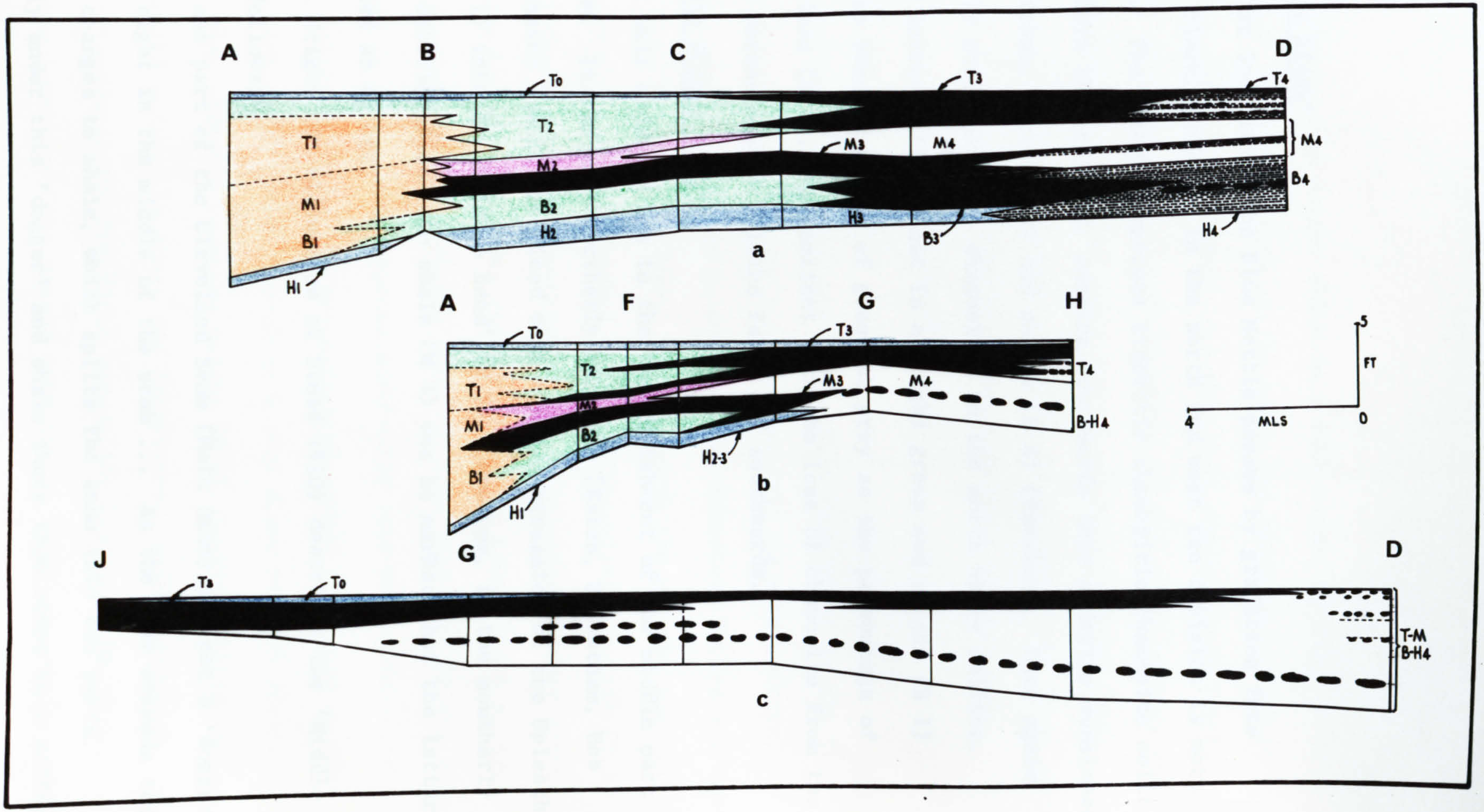
b) Facies

The more important facies comprising the Main Seam and their interrelationship are illustrated diagrammatically in figure 19 . The petrography of each type will be described in greater detail later (page 263).

i) The 'Blue Mottle'

The Blue Mottle is a dark green to grey blue spastolithic siderite chamosite mudstone, the colour of the rock depending upon the percentage of siderite, chamosite and other clay minerals. On the northern escarpment (at Eston, Cliff Rigg and Hutton Lowcross) chamosite is dominant (H 1), but throughout the rest of the ore field siderite becomes more important (H 2,3). The exposure at Brackenberry Wyke, Staithes is typical of the sideritic facies, and also abounds with the diagnostic Rhizocorallium. Between Kettleness and Hawsker and between Ayton Mine and Botton Head the Blue Mottle passes into sideritic shale (H 4) and looses its identity.

FIG. 19. CROSS SECTION OF MAIN SEAM.



ii) '<u>Bottom Block</u>'

In most localities the Blue Mottle passes by gradation into the Bottom Block, although in the north and west the division is more pronounced. The latter comprises sideritic chamositic chamosite oolites (B 1,2) within the orefield, passing southwards into siderite mudstones (B 3) (Staithes, Kettleness) and shales (B 4) (Hawsker). Once again this unit is noticably more chamositic in the north where ooliths, shells and intraclasts are set in a bright green mud matrix (B 1) which passes through shades of greenish grey as the percentage of siderite rises (B 2). Concomitant with the loss of chamosite from the matrix the percentage of ooliths falls off southwards.

iii) '<u>Middle Dogger Band</u>'

This unit develops due to the impoverishment of the middle part of the seam. In the most northerly sections (Eston, Upleatham, Hob Hill) it passes almost unnoticed with the transgression of the Upleatham facies (B 1) into the 'Middle Band' (M 1). However, in the southerly mines the deterioration into shale (M 4) was so marked that the latter was rejected as an ore.

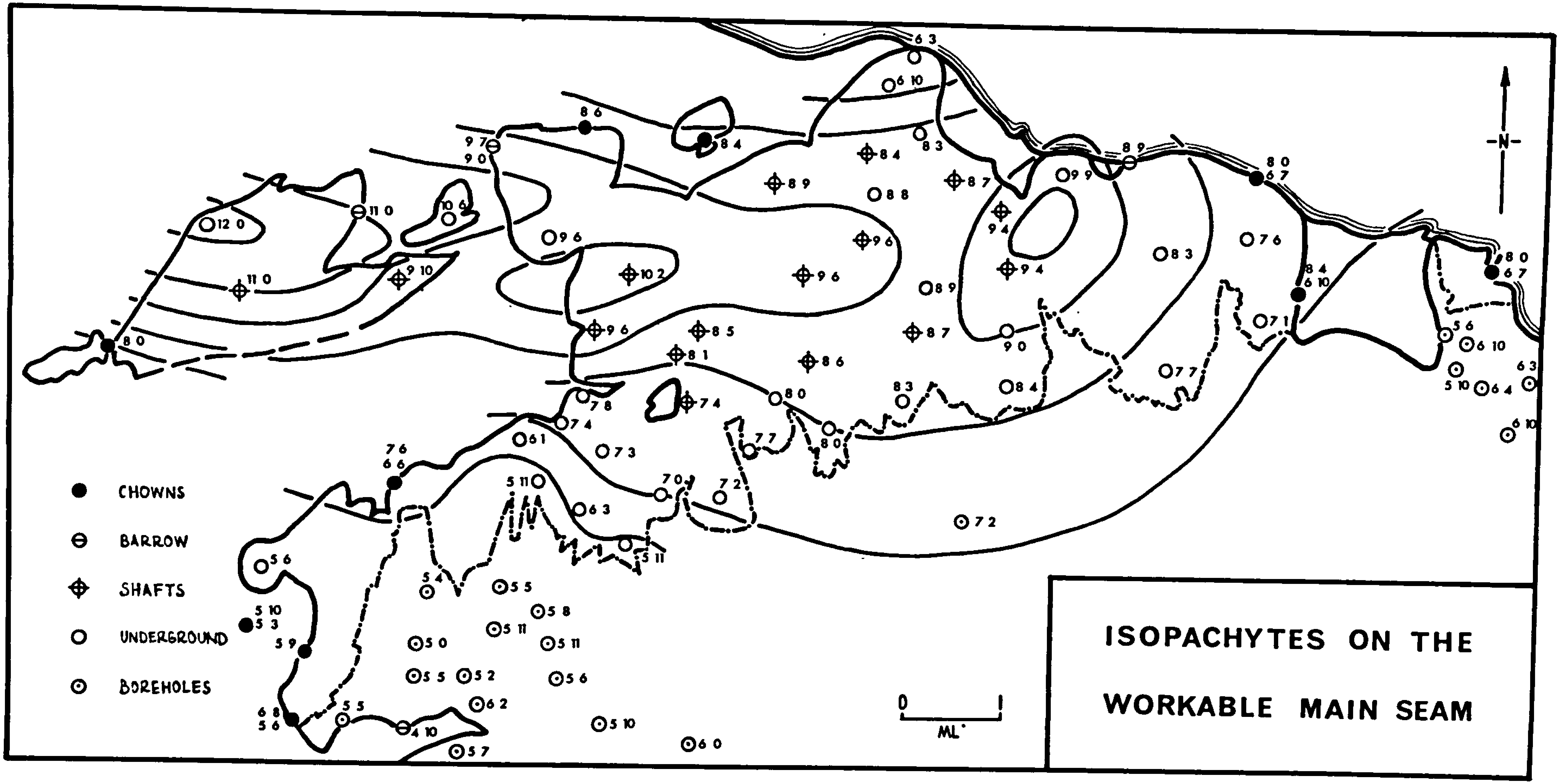
H.E. Wright (in discussion of Stead 1910) describes the 'Middle Band' as follows:-

"In one part of the Cleveland Seam (Main Seam) you get a 'dogger' coming in right in the middle of the seam ... As the seam extends this gradually changes to shale, which splits the seam into two parts. Immediately under this 'dogger' and shale there then comes in a different material, a hard brown dogger which is a rich stone, we find it is almost always the richest part of the seam, but again as you go further on, the shale band gets thicker, and then this dogger becomes split up by bands of shale until the whole bottom of the seams becomes very poor." The first 'dogger' to which Wright refers is a dark green spastolithic sideritic chamositic mudstone (M 2), while the 'dark brown dogger' is a siderite mudstone (M 3) which appears persistantly immediately above the Bottom Block.

iv) 'Top Block'

The highest energy deposits in the Main Seam occur in the Top Block. By comparison with the 'Bottom Block' it is more oolitic, intraclastic and shelly, and in addition the ironstone facies are more extensive than in any other unit. In the north the greater part of the Block consists of crossbedded, shelly, intraclastic oolite (T 1) apparently derived by the reworking of older deposits further north. Falsebedding has also been described by Tate and Blake (1876,p. 120) from Kirkleatham and was probably observed from this part of the seam. This facies is overlain and passes southwards into non-crossbedded chamosite oolite (T 2) as the percentage of matrix increased at the expense of the grain total. South of a line drawn between Staithes and Ayton Mine siderite mudstone enters (T 3), interdigitating with poor chamosite oolites in these two localities. A thin siderite mudstone persists in the Top Block evenin the Blackmoor sections, although the lower part has passed into shale. Only at Hawsker, however, does the Block pass entirely into shale.

FIG. 20.


ISOPACHYTES ON THE
WORKABLE MAIN SEAM
N
CHOWNS
BARROW
SHAFTS
UNDERGROUND
BOREHOLES
0
ML

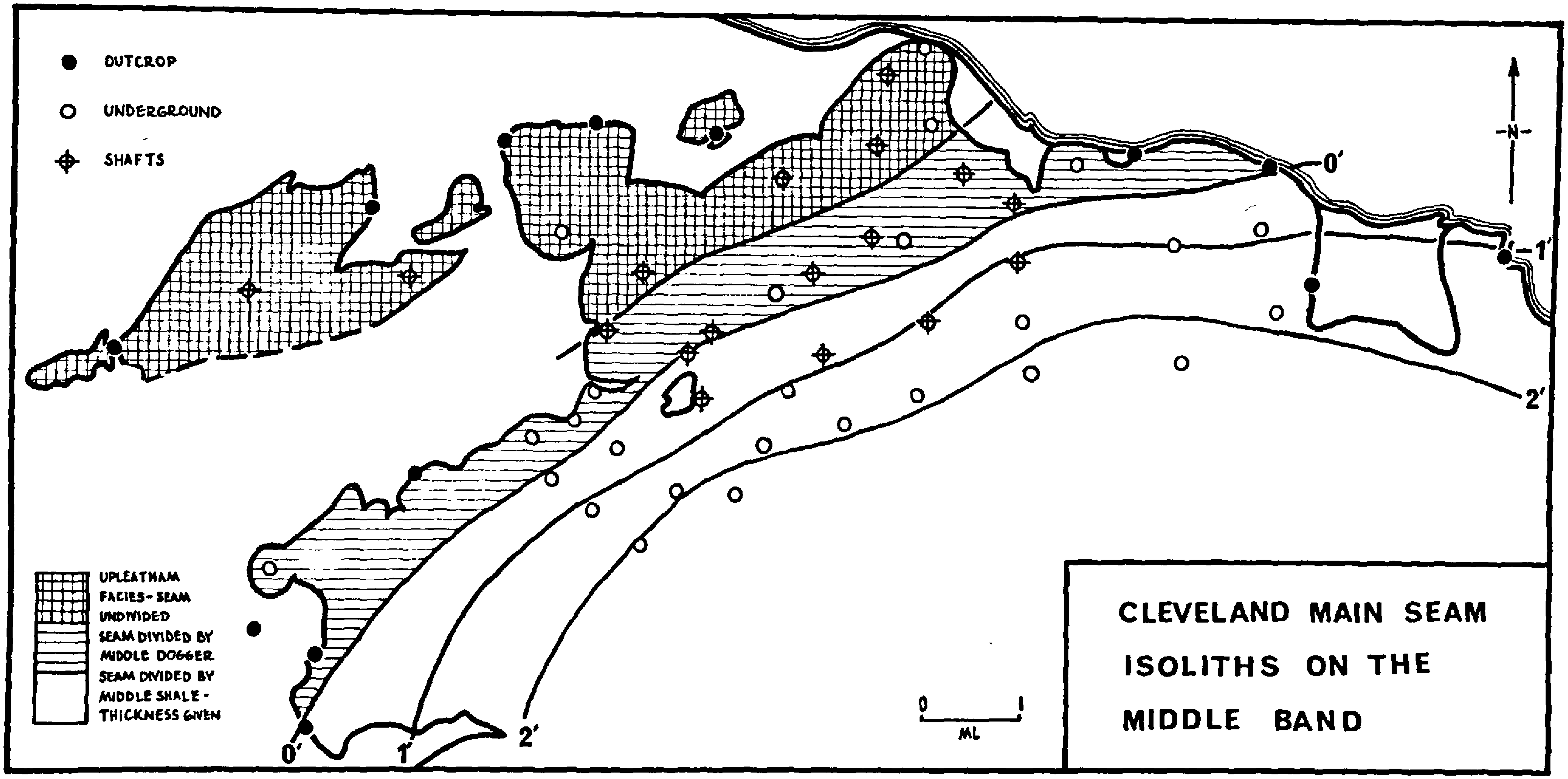
c) Relationships between facies and thickness

In general it may be stated that the thickness, facies and ore tenor of the Main Seam change most rapidly in a north-south direction, and are most uniform from east to west. However, thickness and facies are not entirely interdependent, so that the isopachytes and isolithic lines are slightly discordant. Throughout the orefield the trend of the isopachytes is west north west- east south east (fig. 20) whereas the isolithic lines run east north east-west south west. It is this trend which is shown by Barrow's (1880, 1888) 'shale line' and the shale isoliths drawn by Lamplugh et al. (1920) (see fig. 21).

4. Palaeontology and Palaeoecology

The Cleveland Main Seam has yielded a prolific fauna through the work of Tate and Blake (1876, p. 154) and the reader is referred to this for a complete list. However, it should be pointed out that the definition of the Main Seam was somewhat different previous to the work of Barrow (1888) so that part of this list would now be ascribed to the Upper *Pecten* Seam. This is particularly the case with the brachiopods which, with the exception of *Tetrarhynchia tetrahedra*, are mainly derived from the Eston Shell Beds (page 53). More recently the fauna of the *spinatum* zone as a whole has been summarised by Hallam (1967, p. 400) and compared with that in the Midlands, Southwest England and the Hebrides. Hallam (op. cit.) pays particular attention to the palaeoecology of the *spinatum* beds in Yorkshire.

FIG. 21.



OUTCROP
UNDERGROUND
SHAFTS
UPLEATHAM FACIES - SEAM UNDIVIDED
SEAM DIVIDED BY MIDDLE DOGGER
SEAM DIVIDED BY MIDDLE SHALE - THICKNESS GIVEN
N
0'
1'
2'
0 1
ML
CLEVELAND MAIN SEAM
ISOLITHS ON THE
MIDDLE BAND

Following the practice adopted in the earlier sections the fauna may be divided as follows:-

(i) Nekton - ammonites particularly abundant in the Top Block, belemnites.

(ii) Epifauna - the epifaunal assemblage is much the same as in the other seams including *Pseudopecten*, *Entolium*, *Oxytoma*, *Liostrea*, and *Plicatula* in various stages of comminution and all disarticulated, together with occasional specimens of *T. tetrahedra* (usually articulated).

(iii) Infauna - Hallam (op. cit.) makes a distinction between shallow infaunal elements such as *Nuculana*, *Pseudotrapezium*, *Protocardia* and *Tutcheria*, all small species, generally reworked, partially disarticulated and comminuted to various degrees, and the deep infaunal burrowers including *Gresslya*, *Pleuromya* and *Ptoladomya*, which occur articulated in their positions of life. Trace fossils are also abundant including *Chondrites* and at least two types of *Rhizocorallium* probably attributable to burrowing crustaceans (Häntzschel 1962).

Type i) consists of plugged 'U' shape, 'spreiten' burrows, parallel or slightly oblique to the bedding, up to a maximum of about 15 cm. long with a tube diameter of between 0.5-0.75 cm. and gauge guage of 2.5-3.5 cm. (fig. 22c). The 'U' tube is always filled with siderite mud and appears unornamented, while the lithology of the 'spreite', which marks the stages in the protrusion of the burrow through the sediment (Seilacher

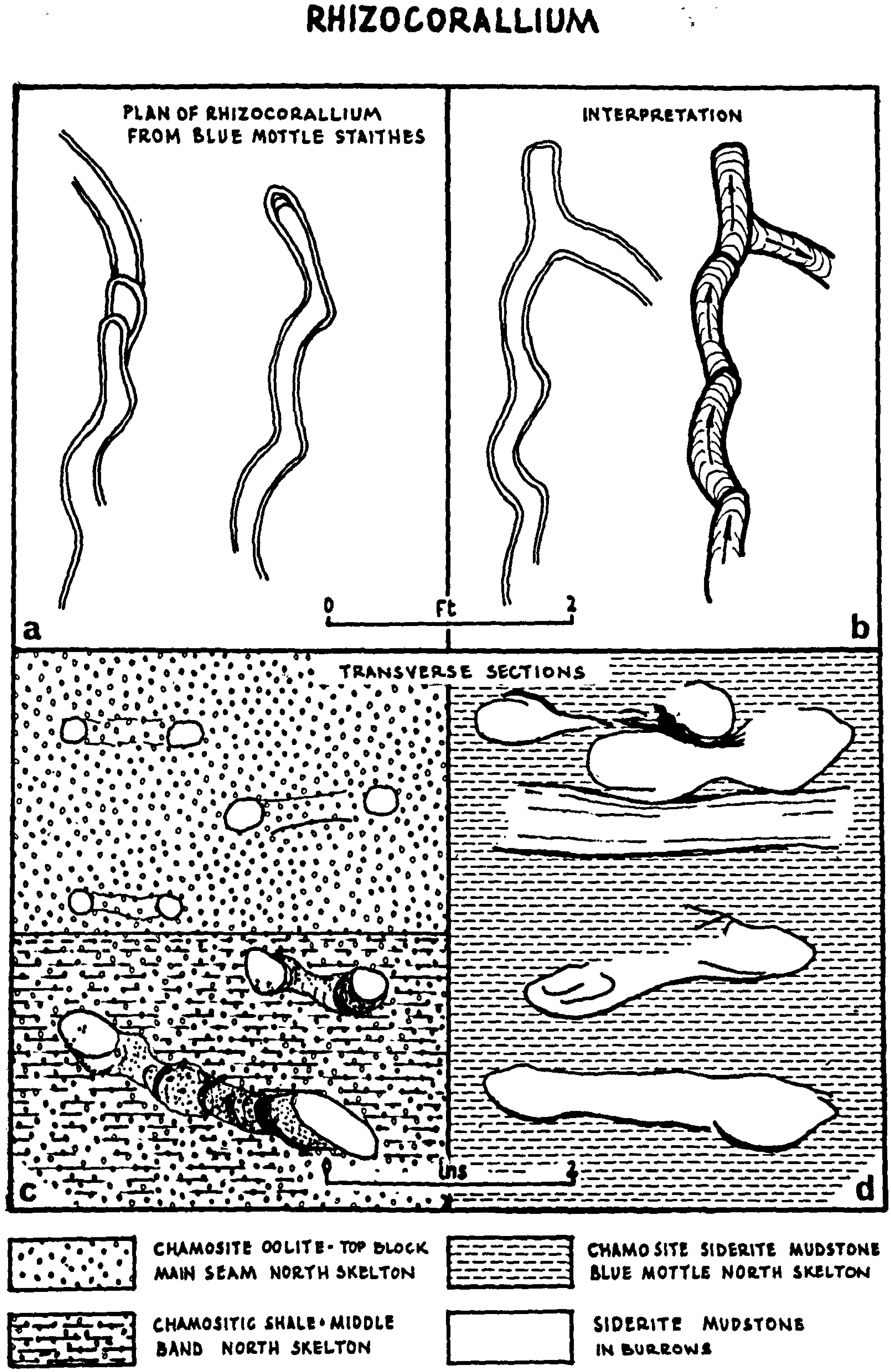


FIG. 22. RHIZOCORALLIUM BURROWS.

1967) depends largely on the lithology of the surrounding rock. Usually the more inhomogeneous the rock the better preserved the 'spreite'. This type is most common and best preserved in the Top Block.

Type ii) consists again of plugged 'U' shaped 'spreiten' burrows, parallel or slightly oblique to the bedding but the dimensions are larger; observed up to 1 metre, but probably longer, tube 1.5-1.8 cm. in diameter, guage 5-6 cm. (fig. 22d). The tube is always filled with siderite mudstone and ornamented with scratch marks, but the structure of the 'spreite' is usually lost, probably through compaction. The sinuosity of the burrows seen in plan suggests some kind of periodicity in the protrusion of the burrowing animal within the sediment (fig. 22ab).

Farrow (1966) has suggested that the presence of Rhizocorallium in the Main Seam may be taken to indicate a shallow sub-tidal environment, a conclusion which is endorsed by the palaeoecology of the bed as a whole.

5. Conclusion

Economically the Cleveland Main Seam was until recently the most valuable stratum in north-east Yorkshire and one of the foremost Phanerozoic sedimentary iron ores in the world. The nature of the facies arrangements described briefly above indicate that the seam represents the lithified deposits of an approximately east-west trending oolite shoal complex and its offshoal equivalents, comparable with the better known oolitic limestone complexes.

The whole question of the origin of the Cleveland Main Seam will be discussed in greater detail later (page 307).

V HAWSKERENSE BEDS

The strata between the top of the Main Seam and the base of the Upper Lias (bed 51, Staithes) are assigned to the hawskerense subzone of the spinatum zone. A total of 8'5" of strata were included at the type section in Brackenberry Wyke, Staithes by Howarth (1955) but this thickness is reduced by the present author on the supposition that the Sulphur Band (bed 52 Staithes) represents the first transgressive deposit of the tenuicostatum zone of the Upper Lias.

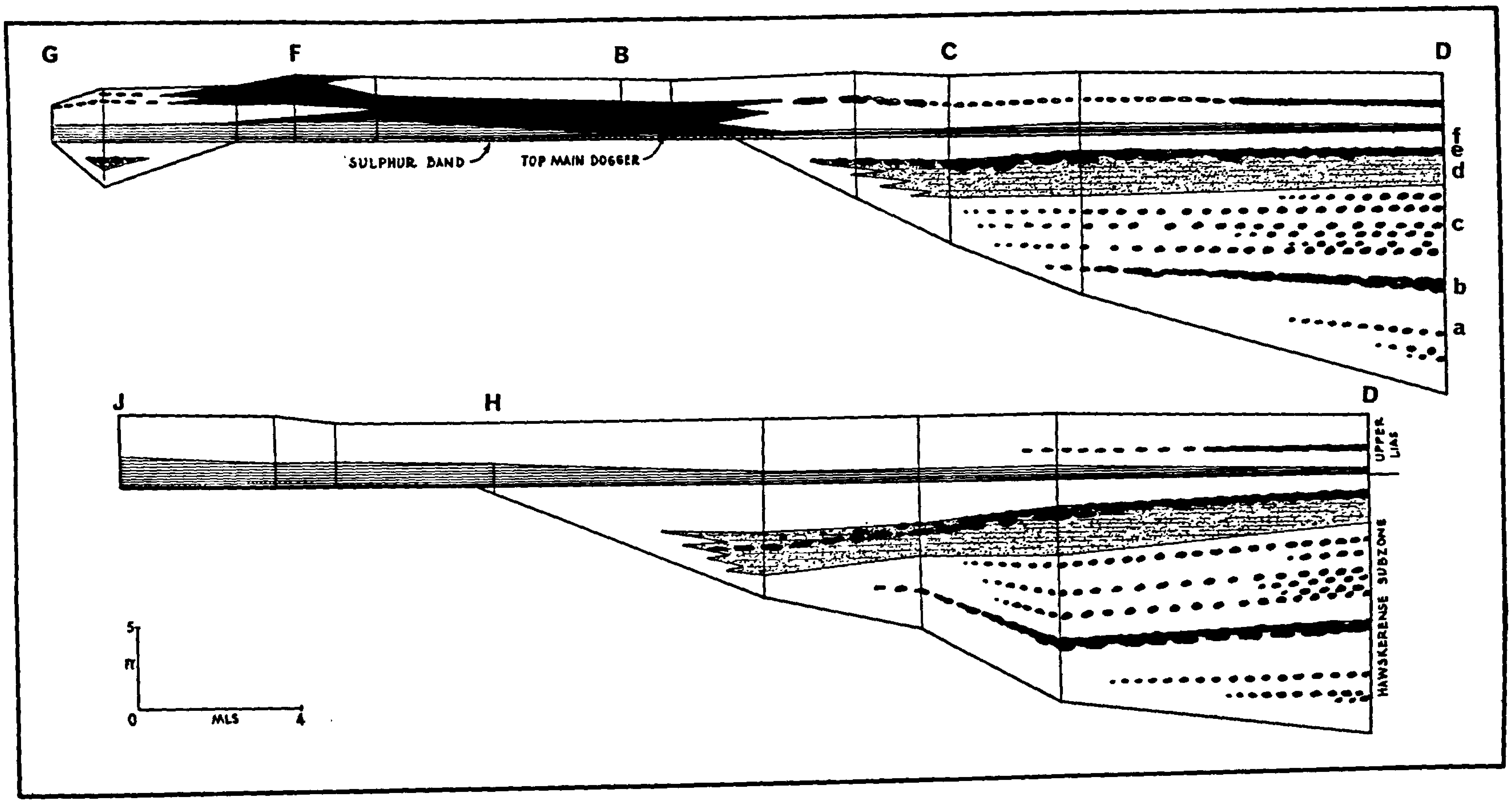
Details of the stratigraphy of both the hawskerense beds and the basal beds of the Upper Lias are summarised in enclosure 3 .

A. THE HAWSKERENSE SHALES

1. Type Section

In Brackenberry Wyke the hawskerense shales are 6'7" thick. The Main Seam is directly overlain by medium grey silty shales (units a-c) which pass upwards into light grey silty shales with impersistant ripple marked calcareous siltstones (d). However, for the most part the sedimentary structures within the shales have been destroyed by the trace fauna. During diagenesis siderite was segregated to form small nodules only an inch or two across, as well as the tabular concretions of bed 51 (unit e). According to its precise horizon, which varies slightly this siderite mudstone engulfs large numbers of the smaller concretions and also encroaches upon a bed of calcite mudstone nodules with Pleuromya costata. The latter is separated from the base of the Upper Lias by 1'6" of medium grey silty shale once again with small siderite mudstone nodules (unit f).

FIG. 23. CROSS SECTION OF HAWSKERENSE BEDS



2. Lateral variation (figure 23).

a) Thickness

The *hawskerense* beds reach a maximum observed thickness of about 17 feet in Howdale Gill (16'2" at Hawsker Bottoms), and wedge out rapidly north-westwards along the coast (fig. 23a) and westwards through Eskdale into Blackmoor. They may be traced as far north as Rockcliff, and in the west as far as Bransdale and Baysdale, but it is clear that over the greater part of the northern orefield as well as in the west these beds are completely absent, in which case the Upper Lias oversteps onto the *apyrenum* beds.

From an examination of figure 23 it may seem that the attenuation is entirely contained within the *hawskerense* shales and has nothing to do with Upper Lias transgression. In detail the attenuation appears greatest in the lower beds, which are successively overlapped by those above, so that the *hawskerense* shales were deposited as the result of a marine transgression over the oolitic ironstones of the Main Seam. Significantly this transgression began in the south-east, in the region of deepest water sedimentation during *apyrenum* times, and died out almost entirely over the area of shallow water oolitic shoals.

b) Facies

The lithology of the type section is characteristic of the *hawskerense* beds in their thinner developments, but as the succession thickens its components, especially unit d, become more silty and units a-c are split by siderite mudstone nodules.

With increasing silt content in the south-east the impersistant calcareous siltstones of unit(d)at Staithes, Kettleness and Grosmont, become continuous at Hawsker. Despite strong reworking by Chondrites ripple marks and crosslamination are preserved in some places. The strongest siderite mudstones occur at horizons (b) and (e). In their maximum development at Hawsker, Kettleness and Grosmont, they are compounded of double or even treble siderite mudstone concretions forming an entire bed, capped in places by areas of calcite cone-in-cone. However, as the succession thins the component nodules gradually separate and become discrete before dying out. As with the subnodosus and lower gibbosus beds it is important to note the association between silty shales and siderite mudstone nodules, suggestive of a correlation between grain size and iron content.

3. Palaeontology and Palaeoecology

The most fossiliferous horizons in the lower hawskerense beds are the nodule horizons (b) and (e), from which the faunal list (Table 6) was largely compiled. Within the silty shales the fauna is much less abundant. Trace fossil activity is present throughout the beds but is particularly striking in unit (d) which contains Arenicolites, Chondrites and Rhizocorallium. From the top of this bed the cast of a tree trunk 75 feet long was observed at Hawsker Bottoms.

By far the dominant ecological group is the burrowing lamellibranchs Pholadomya, Pleuromya and Unicardium; all but the latter preserved in their position of life. They occur throughout the succession but

Table 6.

Palaeontology of the _hawskerense_ beds

Ammonites

Amauroceras ferrugineum

Pleuroceras hawskerense

Belemnites

Lamellibranchs

Pholadomya ambigua

Pleuromya costata

Pseudopecten equivalvis

Unicardium subglobosum

Brachiopods

Tetrarhynchia tetrahedra

Pentacrinus

Arenicolites, _Chondrites_, _Rhizocorallium_

wood.

(see also Tate & Blake 1876, p. 126-7, 128, 130) especially at horizons (b) and (e). These two horizons are also the chief repositories of broken and disarticulated epifaunal genera, which with the exception of Pseudopecten are rare in the succession as a whole, and of the nektonic ammonites and belemnites.

The faunal assemblage of the hawskerense beds is very distinctive and quite unusual by comparison with the shales of the subnodosus, gibbosus and apyrenum subzones. The dearth of epifaunal species especially the usual thin shelled forms such as Limea and Oxytoma inequivalvis is especially characteristic. In the lack of these forms the fauna comprises two main elements:-

(i) The Nekton including abundant ammonites.

(ii) Infaunal lamellibranchs mainly in their positions of life.

The abundant nekton is taken to indicate conditions of slow deposition, especially marked at horizons (b) and (e), which are particularly fossiliferous. The thorough reworking to which these beds have been subjected also appears to substantiate this view. Both the absence of epifaunal genera, and the development of ripple marked calcareous siltstones probably indicate higher current velocities than those usual in the shales of the Ironstone Formation, but clearly the sea bed was sufficiently stable to enable colonisation by infaunal lamellibranchs.

4. Environment of Deposition

The silty shales of the hawskerense subzone appear to represent a late Domerian transgression into the Yorkshire basin from the south east probably resulting because of renewed subsidence following the deposition of the Main Seam. Both sediments and fauna suggest slow deposition under shallow water conditions, possibly even intertidal at times.

B. THE UPPER LIAS TRANSGRESSION

Because of the dearth of ammonites in the basal beds of the *tenuicostatum* zone Howarth (1955) found difficulty in fixing the exact position of the Middle Lias-Upper Lias boundary. However, there are now strong reasons for regarding the Sulphur Band and its equivalents (bed 52 Staithes) as the basal bed of the Upper Lias.

(i) This horizon although it averages only six inches in thickness is sufficiently distinctive to be traced throughout Cleveland, and proves to be highly transgressive with respect to the *hawskerense* and *apyrenum* beds (see fig. 23).

(ii) Outside the Northern Orefield the bed is a fissile shale consisting of graded laminations of fine sand passing upwards into bituminous shale, the whole being impregnated with pyrite. The laminations vary in thickness between about 1 mm. and 3 mm. and partake the character of varves (see pages 197-198). According to Hallam (1967b) such deposits are often indicative of shallow water marine transgressions.

(iii) Although specimens of *Pleuroceras* occur fairly abundantly in the *hawskerense* shales up to the Sulphur Band they are completely absent above; the first *Dactylioceras* makes its appearance 4'2" above this bed at Hawsker Bottoms, approximately 2 feet below the lowest occurrence recorded by Howarth (op. cit. p. 154).

(iv) On the northern escarpment the 'Top Main Dogger' lying immediately on top of the Sulphur Band contains abundant Gibbirhynchia tiltonensis, a brachiopod previously only found in abundance in the 'Transition Bed' of the Midlands and apparently confined to the lowermost beds of the Upper Lias in Britain (Ager 1954, p. 47). The present material has been kindly examined by Dr. Ager who confirms the author's identification.

In the northern part of the area where the Upper Lias oversteps onto the Main Seam, the basal two to three feet of Upper Lias shales including the Sulphur Band itself become increasingly ferruginous, develop siderite mudstone nodules and eventually pass into chamositic siderite mudstones, with occasional ooliths, known throughout the northern ore field as the 'Top Dogger' and used as a roof in the workings. The Sulphur Band itself consists of a pyritic oolite in the north and west of the area, where the hawskerense shales are missing and appears to arise directly as a result of the superimposition of the Upper Lias on the Main Seam (see pages 197-201). The nature of this junction formerly so well exposed in the ironstone mines can now only be examined at a few localities on the western and northern escarpments at Cod Beck, Osmotherley; Scugdale; Raisdale; Botton Head and at the Ayton Mines.

VI CONCLUSION

The succession in north-east Yorkshire, up to a maximum of over 1400 feet thick, is one of the best developed, most complete successions of the Lias in Britain, and indicates the existence of gently subsiding basin of deposition known as the Yorkshire Basin. Of this thickness the Domerian (Middle Lias) comprises a maximum of about 150 feet divided between the Cleveland Sand Formation below (60 feet) and the Cleveland Ironstone Formation above (up to 90 feet thick).

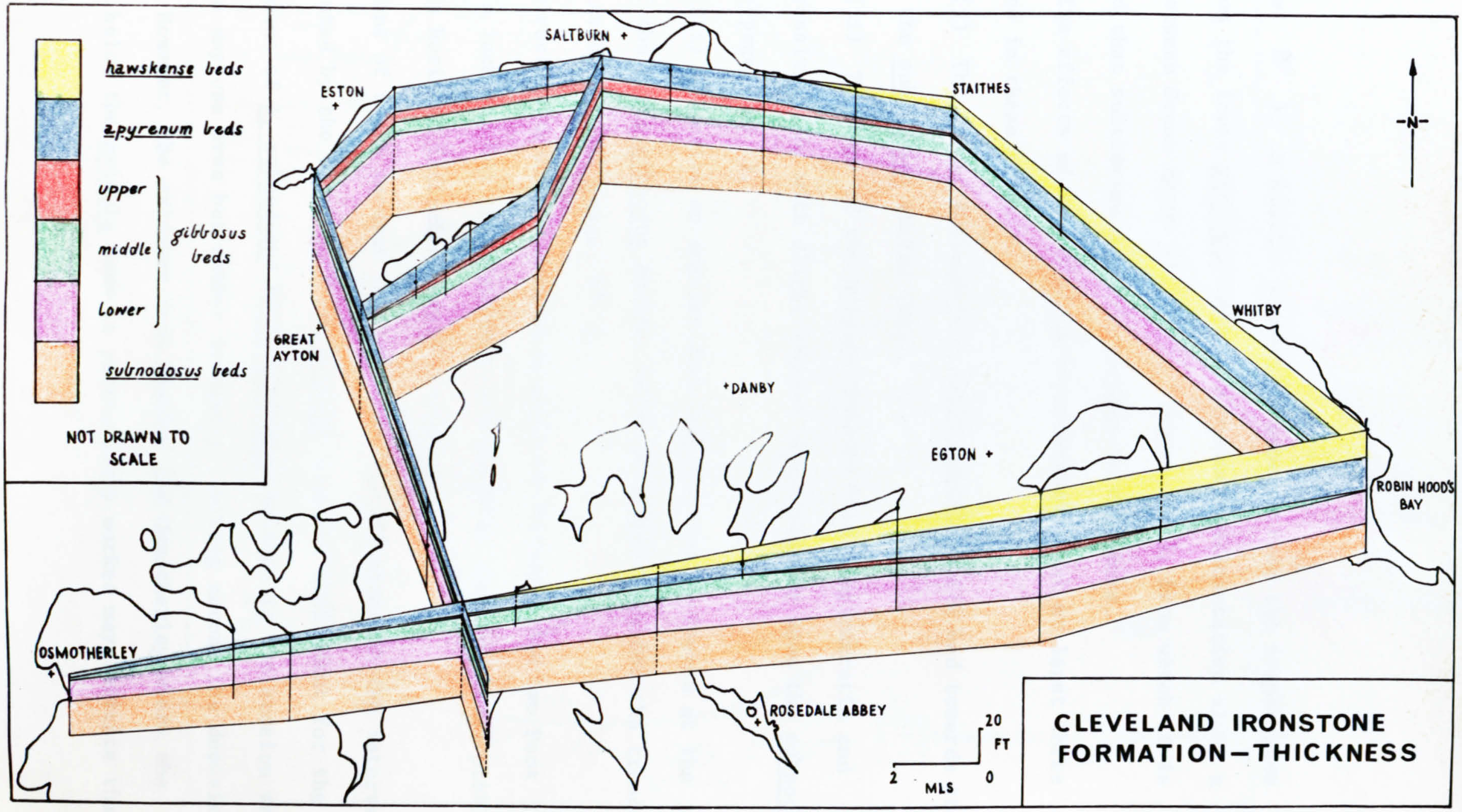
Two factors are shown to contribute to the distribution of thicknesses in the Ironstone Formation. The first is the thickness of sediment deposited, which may be taken as an indication of relative subsidence and the second the amount of penecontemporaneous (i.e. intra Liassic) erosion, which is correlated with uplift taking place in the basin.

A. THE THICKNESS OF THE UPPER MARGARITATUS ZONE

The thickness of the upper *margaritatus* beds (subzones of *A. subnodosus*, and *A. gibbosus*) is dependent more than anything else upon the extent of erosion at the *margaritatus*-*spinatum* junction, which tends to obscure the depositional variations especially in the *gibbosus* beds.

During *subnodosus* times deposition appears to have been at a maximum in the Eston-Guisborough area with the possibility of a trough extending east south east from Guisborough in the direction of Whitby

FIG. 24.



CLEVELAND IRONSTONE FORMATION—THICKNESS

(figure 8). A similar trend also appears from the isopachytes drawn on the lower _gibbosus_ beds with maximum sedimentation along a line between Great Ayton and Whitby (figure 12), from which it is deduced that subsidence was at a maximum in this zone.

The effects of erosion have been determined at at least three horizons in these beds:-

(i) The lowest horizon is a conglomeratic shell bed towards the top of the _subnodosus_ shales (page 24).

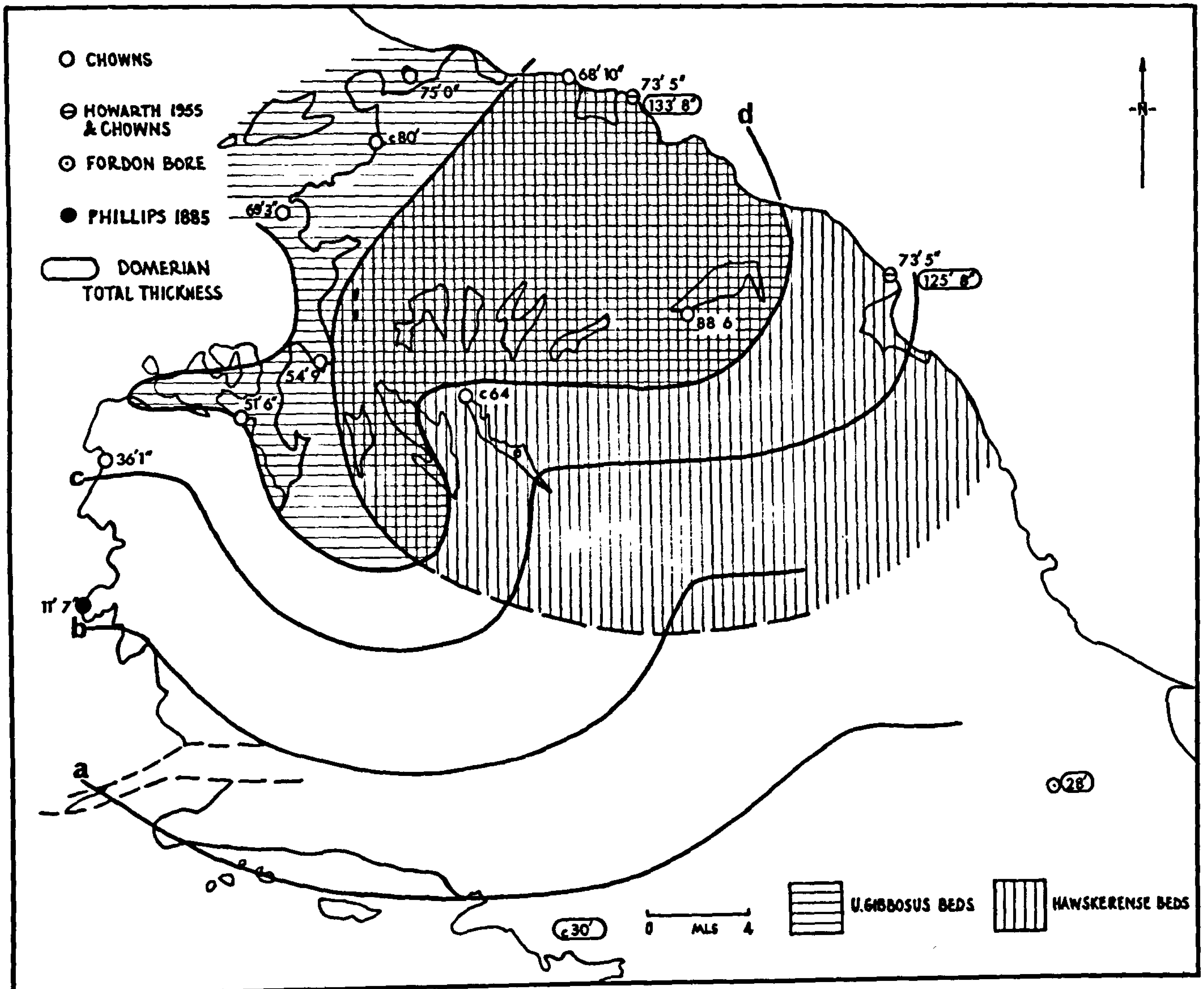
(ii) The base of the _Avicula_ Seam is both conglomeratic and transgressive lying with slight angular discontinuity upon the _subnodosus_ shales (page 24).

(iii) Likewise an angular discontinuity may be traced at the base of the lower _gibbosus_ shales, which is responsible for the truncation oftthe Avicula Seam (pages 33).

Direct evidence for erosion beneath the Raisdale and Two Foot Seams is lacking, but the abundance of belemnites and occasional pebbles at these horizons indicates definite hiates.

None of these lacunae indicate major uplift although the interval represented by the erosion of the _Avicula_ Seam was sufficient for the replacement of _A. subnodosus_ by _A. gibbosus_; neither is the erosion very great in any one area but rather irregular, cutting across the depositional trend. However, the evidence from Hawsker and Osmotherley where the erosion below the _Avicula_ Seam is particularly worked may indicate that

FIG. 25. THICKNESS OF CLEVELAND IRONSTONE FORMATION IN RELATION TO MARGARITATUS-SPINATUM UNCONFORMITY



a. Cut out of Osmotherley Seam

b. Cut out of Avicula Seam

c. Cut out of Raisdale Seam

d. Cut out of Two Foot Seam

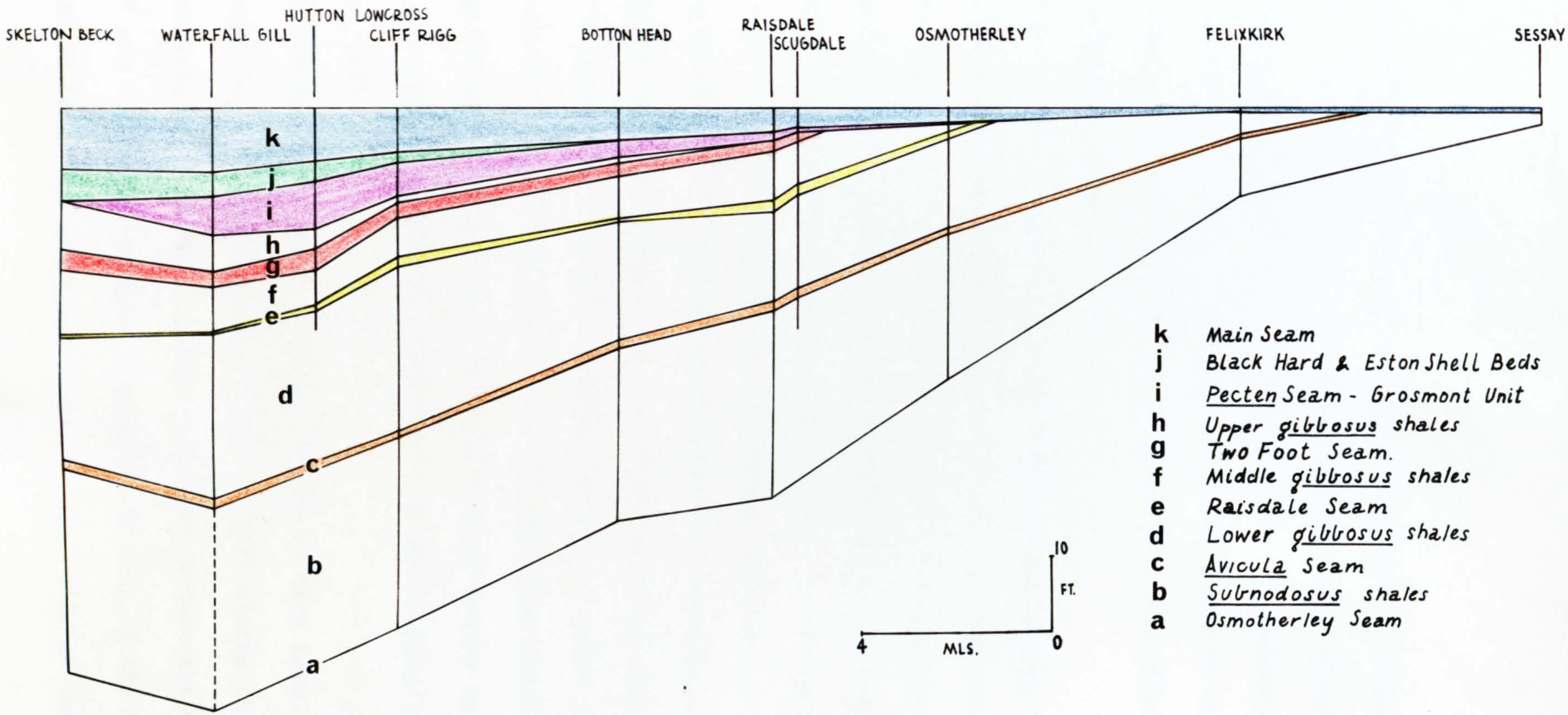
this discontinuity increases in importance south of the present area, especially if Phillip's (1858) section at Felixkirk may be taken to indicate further attenuation in the subnodosus beds below the Avicula Seam. ~~(see appendix).~~

B. THE MARGARITATUS-SPINATUM UNCONFORMITY

Not surprisingly the most important stratigraphic break in the Ironstone Formation occurs at the margaritatus-spinatum boundary. Although quite undetectable in the individual outcrops the existence of a well marked angular unconformity becomes immediately obvious through the truncation of the gibbosus beds as shown in figure 24 .

The connection between the overall thickness of the upper margaritatus zone and the level of downcutting at this unconformity has already been mentioned and is illustrated in figure 24,25. The zone of least erosion, running south east of Guisborough towards Grosmont, it should be noted, coincides approximately with the areas of greatest subsidence in the subnodosus beds and lower gibbosus beds, the amount of erosion increasing to the east, south and west. Figure 26 , a cross-section drawn from the centre of the basin at Skelton Beck along the western escarpment of the Cleveland Hills, as close as possible to the true dip of the place of unconformity, shows the way in which the margaritatus beds are cut out, proceeding southwards. In the Guisborough area the upper gibbosus beds are just over 6 feet thick but diminish fairly continuously until the Two Foot Seam is cut out in the vicinity of Scugdale. The line of truncation may be followed eastwards through

FIG. 26. CROSS SECTION OF YORKSHIRE BASIN.

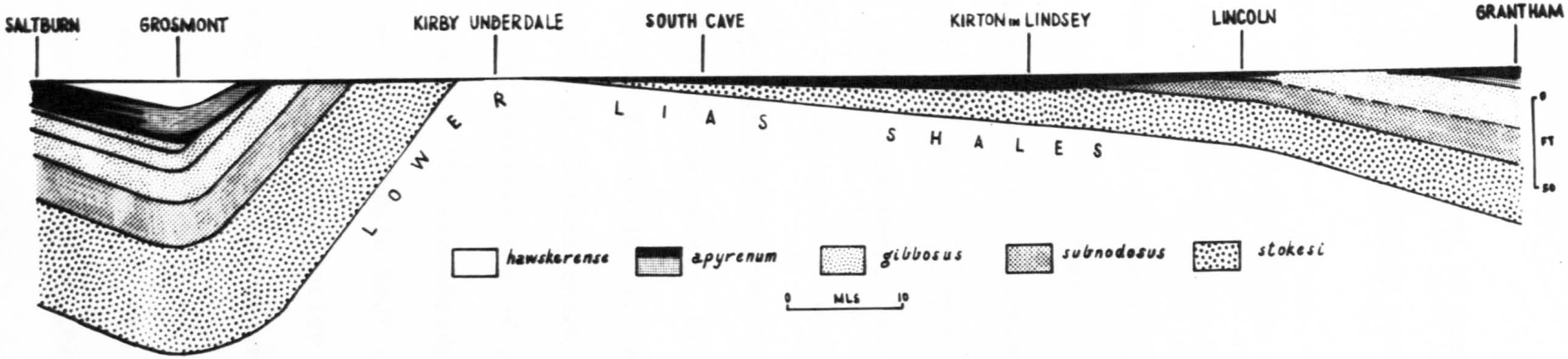


Blackmoor probably emerging at the coast near Whitby (figure 25). In a belt south of this line the spinatum beds rest directly upon the middle gibbosus beds until erosion reaches the Raisdale Seam. On the western escarpment this appears to take place in the neighbourhood of Osmotherley, while on the coast it must occur some distance south of the available outcrops.

Thus the total thickness of the upper margaritatus zone declines from 62'7" at Skelton Beck to 33'11" at Cod Beck, Osmotherley, at the southern limit of the present work. However, from the researches of Tate and Blake (1876) and Fox-Strangways (1892) it is clear that this attenuation is maintained still further south. At Felixkirk, east of Thirsk, the total thickness of the Ironstone Formation is given by Phillips (1858) as 11'7" of which perhaps 11'0" belongs to the upper margaritatus zone ~~(see page)~~. It is possible that the Avicula Seam is represented in Philips' section, but is probably cut out not far south, for in the Sessay area, west of the Coxwold-Gilling gap, the spinatum ironstone rests almost directly upon the sandy beds of the stokesi subzone judging by the information given by Tate and Blake (1876, p. 142).

In the Howardian Hills erosion appears to bite into the Cleveland Sand Formation, for Fox-Strangways (1892, p. 119) states that the Middle Lias "consists in the main of sandy shales and sandstones with calciferous doggers" and "decreases rapidly from about 70 feet in the west to not more than 30 feet " at the River Derwent. The whole of the margaritatus

FIG. 27. CROSS SECTION FROM LINCOLNSHIRE TO YORKSHIRE.



zone has been removed by the time Aclam is reached for here the remnants of the *spinatum* zone sit directly upon the Lower Lias (Kent 1955).

South of the Market Weighton uplift the arrangement of strata is the mirror image of that in the Yorkshire Basin, successively higher beds being revealed beneath the *margaritatus*-*spinatum* unconformity as one proceeds through Lincolnshire (figure 27). Precisely where the *margaritatus* beds reappear south of Market Weighton is unknown, but it is tempting to suggest that the *stokesi* subzone may be represented in the shales below the ferruginous flaggy limestone (with *Pleuroceras*) in the Everthrope railway cutting near South Cave (Fox Strangways 1892). At Kirton-in-Lindsey the *margaritatus* zone has thickened to 18 feet, consisting of grey clays belonging mainly, if not entirely, to the *stokesi* subzone, (Howarth and Rawson 1965). At Lincoln, in the Bracebridge Brick Pits, it is a little over 33 feet thick (Trueman 1918, p.103; Howarth 1957, p. xi) with representatives of all three subzones.

An interesting feature of the Bracebridge section is the occurrence of a bedded ironstone, the "Main Nodule Bed" at the *stokesi*-*subnodosus* boundary, the same horizon as the Osmotherley Seam in Yorkshire. This may also be found in the Grantham area (Woodward 1893, p. 241; Trueman 1918, p. 107) where about 70 feet of clays below the Marlstone have been attributed to the *margaritatus* zone. Trueman (loc. cit.) includes the top 15 feet of these clays in the *spinatum* zone but in the light of Howarth's investigations (1957, p. xi) they probably belong to the *gibbosus* subzone. These beds contain "beds of rubbly ferruginous stone" (Trueman loc. cit.), approximately on the horizon of the Raisdale and Two Foot Seams. Apparently this thickening continues into north Leicestershire where the *margaritatus* beds are said to be between 100 and 120 feet thick (Lamplugh et al. 1909, p. 40) but thereafter the trend is reversed.

The *margaritatus*-*spinatum* unconformity implies substantial uplift in the Market Weighton area, and a major change in palaeogeography, which appears to have been of decisive importance to the development of workable ironstones in the *spinatum* zone both in Yorkshire and the Midlands.

C. THE THICKNESS OF THE SPINATUM ZONE

The changes of thickness and facies which take place in the *spinatum* zone are more complex than those in the *margaritatus*. The zone is divided into three parts as follows:-

(iii)	*hawskerense* shales	(*P. hawskerense*)
	Main Seam	(*P. apyrenum*, *P. hawskerense*)
(ii)	Top Unit, *Pecten* Seam	
	Eston Shell Beds	
(i)	Grosmont *Pecten* Seam	(*P. solare*, *A. margaritatus*)

Although these divisions cut across existing divisions in some respects they are drawn to reflect the most important breaks in the succession. The variation in thickness may be ascribed firstly to an angular disconformity below the Eston Shell Beds, which is seen through the truncation of the basal unit of the zone, the Grosmont *Pecten* Seam (fig. 17); secondly to the depositional wedging of the individual components of the middle unit (figures 16 and 17); and finally to the depositional wedging of the <u>hawskerense</u> shales which show pronounced onlap with respect to the Main Seam (fig. 23).

The area of maximum deposition appears to have varied but from the wedging of the Eston Shell Beds and <u>hawskerense</u> shales, subsidence is presumed at a maximum in the Little Beck area south of Whitby (fig. 25). Although the Main Seam is thickest along the northern escarpment and especially in the Eston-Upleatham district the distribution of ironstone facies (fig. 19) appears to support the contention of deeper water to the south-east. (see pages 263-283). The thickening in the Guisborough and Grosmont areas is also correlated with the incrop of the Grosmont <u>Pecten</u> Seam below the Eston Shell Beds disconformity.

In particular it should be noted that all these maxima lie close to the Guisborough-Whitby line, deduced as the axis of the basin of deposition during upper <u>margaritatus</u> times. The trend is approximately the same as for a large negative magnetic anomaly shown by the Geological Survey aeromagnetic survey (1955), and corresponds in part with the Cleveland Gulf in the underlying Carboniferous (Kent 1966, p. 327; 1967, pl. 1). Both to the north-east and south-west of this line thinning sets in rapidly (figs. 25 and 26). The feather edge of the <u>hawskerense</u> shales is seen in Bransdale, passes west of Baysdale, and then swings eastwards to emerge at the coast near Skinningrove. Thus from an estimated maximum of about 40 feet in the Little Beck area the *spinatum* zone is reduced to 2'2"at Cod Beck, Osmotherley, comprising much reduced representatives of the Main Seam (Top Block) and Grosmont *Pecten* Seam. South of this locality there is no reliable information regarding the thickness of this zone but it appears to persist as a thin oolitic ironstone as far as Kirkby Underdale where the Upper Lias oversteps onto the Lower Lias (Kent 1955).

South of Market Weighton the *spinatum* zone reappears near Goodmanham (Kent 1955) and, then thickens rather irregularly southwards, (fig. 27) until it reaches a maximum thickness of about 30 feet in the vicinity of Melton Mowbray and near Tilton, Leicestershire, (Whitehead et al. 1952, p. 103).

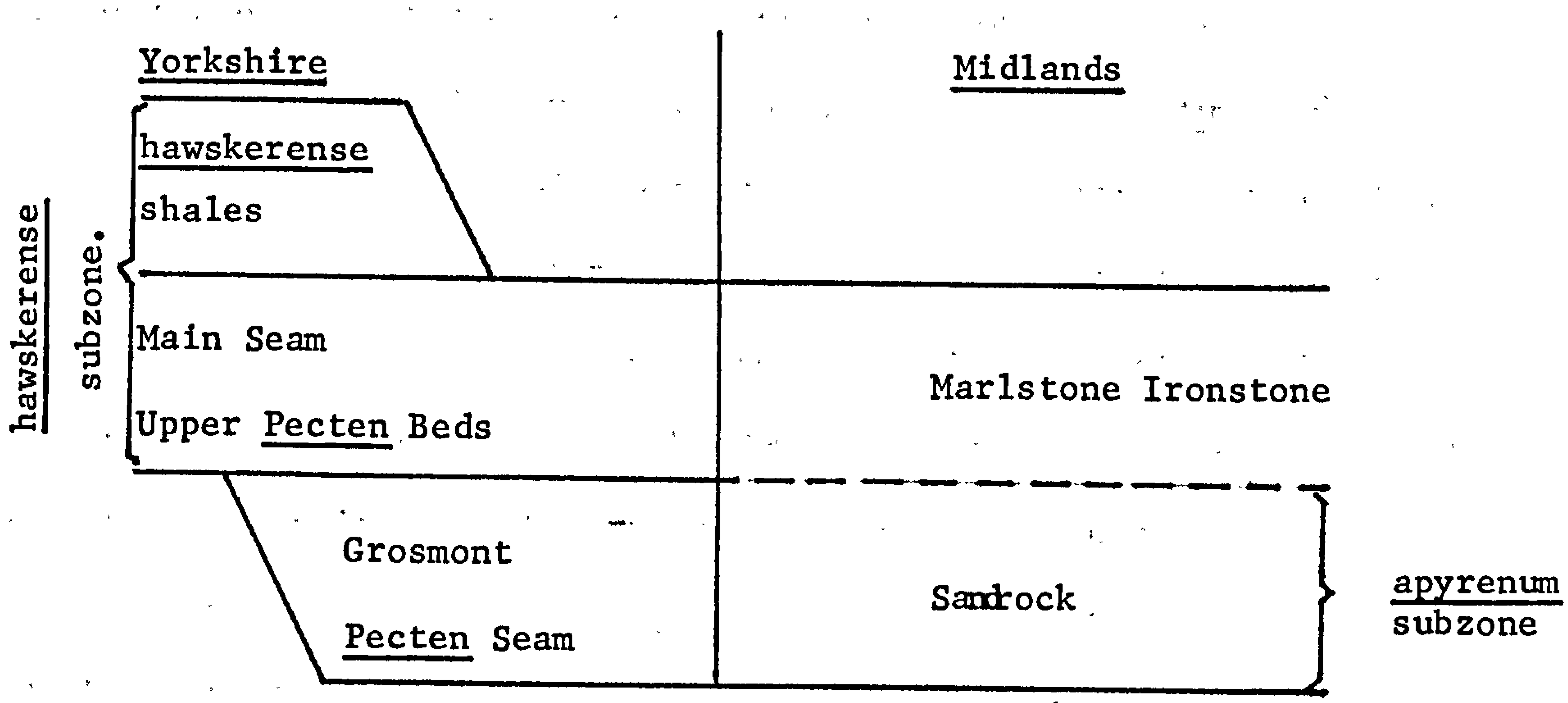
In this region the Marlstone Rock Bed is divisible into two parts, the 'Ironstone' above and the 'Sandrock' below. On lithological grounds these divisions may be said to correspond roughly with the Main Seam and the *Pecten Seam* respectively. However, Howarth (1957, p. x) states that "the sandrock belongs roughly to the *apyrenum* subzone and the Ironstone to the *hawskerense* subzone." This difference of opinion arises because the definition given to the *hawskerense* subzone in Yorkshire (Howarth 1955) is different from that given further south, in Dorset, for example (Howarth 1956). According to Howarth (in Dean et al. 1961, p. 472) the *apyrenum* subzone corresponds with the range of *Pleuroceras solare*, "the lower boundary (of the *hawskerense* subzone) being drawn immediately above the highest *Pleuroceras solare*." The logical position for the *apyrenum-hawskerense* boundary in Yorkshire, therefore, lies at the stratigraphic break below the Eston Shell Beds (page 57), in which case it is legitimate to correlate as follows:-

Main Seam $\simeq$ Marlstone Ironstone $\simeq$ *hawskerense* subzone;

Pecten Seam $\simeq$ Sandrock $\simeq$ *apyrenum* subzone;

but see table 7.

Table 7.



Part of the differentiation noted in the *spinatum* ammonite faunas of Britain (Howarth 1957) may arise from the superimposition of sediments of varying ages rather than from geographical subspeciation. The relative scarcity of *P. solare* in Yorkshire arises because of the truncation of the *apyrenum* subzone, which except for 1½ feet of strata at Hawsker, is completely absent on the Yorkshire coast, although represented inland; the abundance of *P. hawskerense* is correlated with the presence of the hawskerense shales, a rapidly wedging horizon, which may not be represented in Britain outside the Yorkshire Basin.

The thinness of the spinatum zone throughout Britain as a whole, relative to the large number of species of the genus Pleuroceras which occur in these beds testifies to the extreme condensation of the zone.

D. THE DOMERIAN-TOARCIAN JUNCTION

The base of the Toarcian in Yorkshire is marked by a black pyritic 'paper shale' with the distinctive burrows of Arenicolites (bed 52 Staithes; Howarth's 1955 bed 58 non 61). The tenuicostatum zone consists of approximately 30 feet of shale at Staithes (Sylvester-Bradley M.S.) of which the basal 2-3 feet pass llaterally into siderite mudstone (Top Main Dogger) in the northern orefield. In the past this basal horizon has been included with the Domerian (Barrow 1888; Howarth 1955) although no specimens of Pleuroceras are known to occur. However, in the light of the occurrence of Gibbirhynchia tiltonesis in the Dogger and the shales above they are now placed in the Toarcian (pages 74-75).

The succession in Yorkshire is therefore similar to that in the Midlands, the Top Main Dogger being roughly equivalent to the Transition Bed, although without Tiltoniceras acutum.

With the wedging of the hawskerense shales the base of the tenuicostatum zone oversteps onto the Cleveland Main Seam, incidentally giving rise to the Sulphur Band (pages 197- 201). However, despite the importance of the hiatus which this horizon represents and despite a major marine transgression the <u>spinatum</u> beds have suffered relatively little erosion, so that the <u>spinatum</u> ironstones persist as a thin bed well towards Market Weighton. Although slight erosion may have occurred in the Market Weighton area, therefore, the Domerian-Toarcian interval seems to have been one of relative stability in Yorkshire and probably in the Midlands as well (Hallam 1967, p. 398). This accords well with Hallam's contention (1961, 1964, p. 161, 1967, p. 424) that the Lower Toarcian transgression represents a major eustatic rise of sea level.

E. CYCLIC SEDIMENTATION

The alternation of terriginous with chemical sediment seen in the Cleveland Ironstone Formation evinces some kind of periodicity in the evolution of the basin of deposition. The terriginous sediments, shales and silty shales, are on the whole thicker, more uniform in lithology and less fossiliferous than the chemical sediments and appear to have been deposited under quieter deeper water conditions. By contrast the ironstones show by their condensed condition, fauna and granular oolitic texture that they are the product of shallow, moderately agitated water conditions (see pages 300-305).

In the <u>margaritatus</u> zone there is very little preparation in the terriginous sediments before the deposition of an ironstone seam. There is no suggestion of a vertical passage between ironstone and shale, the onset of ironstone formation frequently coinciding with marked breaks in the succession as indicated by the development of pebble and belemnite-shell beds. Only in the subnodosus and lower gibbosus shales is there anything approaching a normal sedimentary cycle with shales passing upwards into silty shales beneath the Avicula and Raisdale Seams respectively. Even so in both cases there is a sharp break below the ironstones, which takes the form of an angular disconformity in the case of the Avicula Seam. No less sharp is the break at the top of the seams; corresponding with the stokesi-subnodosus interval above the Osmotherly Seam and the subnodosus-gibbosus interval above the Avicula; this latter also marked by a slight angular disconformity. The margaritatus ironstones therefore have the appearance of being sandwiched between discontinuities in the shales, formed during a regressive or transgressive-regressive phase of sedimentation.

In the spinatum zone the association between chemical and terriginous sediment is much closer with both vertical and lateral passages between ironstones and shales indicative of small scale rhythms. A major break exists at the base of the Eston Shell Beds and the abundance of belemnites and shells at certain horizons especially in the Pecten Seam, probably indicate hiates in deposition, but they do not effect the pattern of sedimentation substantially. They merely represent an intensification in the process of condensation which was operating throughout the zone.

The small scale alternation between chamositic shale and siderite mudstone, which characterised the Pecten Seam is somewhat reminiscent of the limestone-shale rhythm of the Blue Lias (see for example Hallam 1964).

Since siderite is shown to be a diagenetic constituent of the ironstones (pages 205-233) this is to be regarded as partly secondary in origin. However, there is no suggestion of concretionary segregation, except where these beds pass laterally into shales. It is postulated that siderite is precipitated immediately below the sediment-water interface through the mobilisation of iron in a CO_2 rich zone in the surface layers of the sediment, the rhythm being the result of periodic variations in the oxidising decomposition of organic matter in the sediment (Borchert 1960; and pages 317-319).

Taken as a unit the spinatum ironstones reveal the same kind of relationship as the minor seams of the margaritatus zone: they are sandwiched between the margaritatus-spinatum unconformity below and the spinatum tenuicostatum discontinuity.

Both Hemingway (1951) and Hallam (1961) see the operation of a cycle of regressive sedimentation in the sequence of sediments which make up the Middle Lias, the spinatum ironstones coming as the shallow water culmination before a major marine inundation in the Upper Lias. However, the details of this regression appear rather complex, because of the number of discontinuities in the succession. In particular the highly transgressive nature of the spinatum beds with respect to the margaritatus beds is rather surprising. The main difference between the margaritatus-spinatum unconformity on the one hand and the spinatum-tenuicostatum on the other, however, is that while the former clearly results from local epeirogenic uplift the latter represents a much more uniform and perhaps eustatic change in sea level observable throughout Europe. A combination of epeirogenic and eustatic effects may be responsible for the Middle Lias cycle of sedimentation therefore, the more local effects being superimposed on the major eustatic change.

CHAPTER II PETROGRAPHY OF THE BEDDED IRONSTONES

I <u>INTRODUCTION</u>

The succession of the Cleveland Ironstone Formation consists of an alternation of clastic sediments (shales and siltstones) with chemical sediments (the ironstones). Throughout the succession as a whole clastic sediment is dominant, the percentage of bedded iron ore in any section rarely exceeding 20 percent. Of this the majority falls within the <u>spinatum</u> zone, which in the vicinity of Eston comprised 100 percent workable ironstone. In the two subzones of the <u>margaritatus</u> zone the percentage of ironstone never rises above 10 percent.

Of these sediments only the ironstones of the Cleveland Main Seam have previously received petrographic attention to any extent (Sorby 1856, 1906, Stead 1910, Hallimond 1925, Dunham in Whitehead et al. 1951).

<u>Note on terminology</u>

James (1966), following popular usage makes a distinction between:-

<u>iron formation</u> - banded, cherty, sedimentary iron ores of Precambrian and Palaeozoic age

and <u>ironstone</u> - sedimentary minette ores, clay ironstones, bog iron ores etc. of Phanerozoic age.

The Jurassic iron ores of Great Britain, the Cleveland ironstone seams included, are typical of this second group.

The following chapter is concerned only with the bedded ironstones; beds of primary iron sediment and their diagenetic derivatives.

II CLASSIFICATION

The most valuable classifications are those "based as fully as possible on descriptive parameters but into which genetic interpretations are carefully blended, where they can be reasonably inferred" (Ham and Pray 1962, p. 7). The two most important attributes of any group of rocks are their composition and texture (original and diagenetic).

The composition of ironstones is usually expressed mineralogically (for example Hallimond 1925, Taylor 1949, Brown 1964) or occasionally chemically in assessing the economic potentiality of an ore (Taylor 1949). At the present time composition in terms of grain type, although widely used for limestones (Folk 1959, 1962, Leighton and Pendexter 1962, Plumley et al 1962, Powers 1962, Imbrie and Purdy 1962) has only been of secondary importance for ironstones.

Textural parameters such as size, sorting, rounding and packing have been little used, although once again they are important considerations in the majority of recent limestone classifications (Folk 1959, 1962, Leighton and Pendexter 1962, Plumley et al 1962, Dunham 1962, Powers 1962, Thomas 1962).

A. CLASSIFICATION BY MINERAL FACIES

1. General

The most satisfactory means for the primary classification of bedded iron ores is provided by their mineralogical associations. These may be used in erecting either a qualitative or quantitative description of different ore types upon which a depositional environment may be inferred in terms of Eh and pH (Krumb~~the~~ein and Garrels 1952, Huber and Garrels 1953).

Most important are the iron minerals themselves, since they are directly dependent upon Eh. The following facies of iron, each characterised by a number of possible mineral species, may therefore be recognised (James 1954). They are listed in order of decreasing oxidation-reduction potential.

a) Oxide facies - haematite, magnetite, goethite, limonite.

b) Silicate facies - glauconite, ferric chamosite, ferrous chamosite, greenalite, etc.

c) Carbonate facies - siderite.

d) Sulphide facies - pyrite, etc.

Iron minerals from different facies are invariably associated within the same ore bed and even within the same thin section, because of the overlapping of mineralogical facies during deposition or diagenesis. Thus single phase deposits are rare, two or three phase deposits being the general rule (Caillère and Kraut 1954). The most common combinations occur between facies of related Eh, complex three or four phase associations indicating a complicated depositional and/or diagenetic history. It is probable that each facies is capable of developing either syngenetically or diagenetically, but the weight of evidence suggests that the iron oxide-hydroxide facies is mainly syngenetic, and the sulphide facies mainly diagenetic, while the silicate and carbonate facies may accumulate in either way.

The gangue minerals which occur in association with the iron minerals include both terriginous clastics (quartz and clay minerals) and a wide variety of non-terriginous minerals derived either syngenetically or diagenetically. Calcite together with oxides, hydroxides and carbonate of manganese may be introduced in large quantities at the time of deposition and subsequently; the leaching of iron from the silicate facies may give rise to new clay minerals. By the addition of terriginous minerals ironstones pass into sandstones, siltstones and shales, and by an increase in calcite into limestones. Apparently manganese minerals are only present in small quantities in British and American ores, but are widely reported from sedimentary ores in Russia (Sokolova 1964). By an increase in manganese, iron ores may pass over into manganese ores. There are therefore a large number of possible ore types. The range of variation encountered in British ores may be represented diagrammatically by a pyramid having at its apex terriginous minerals

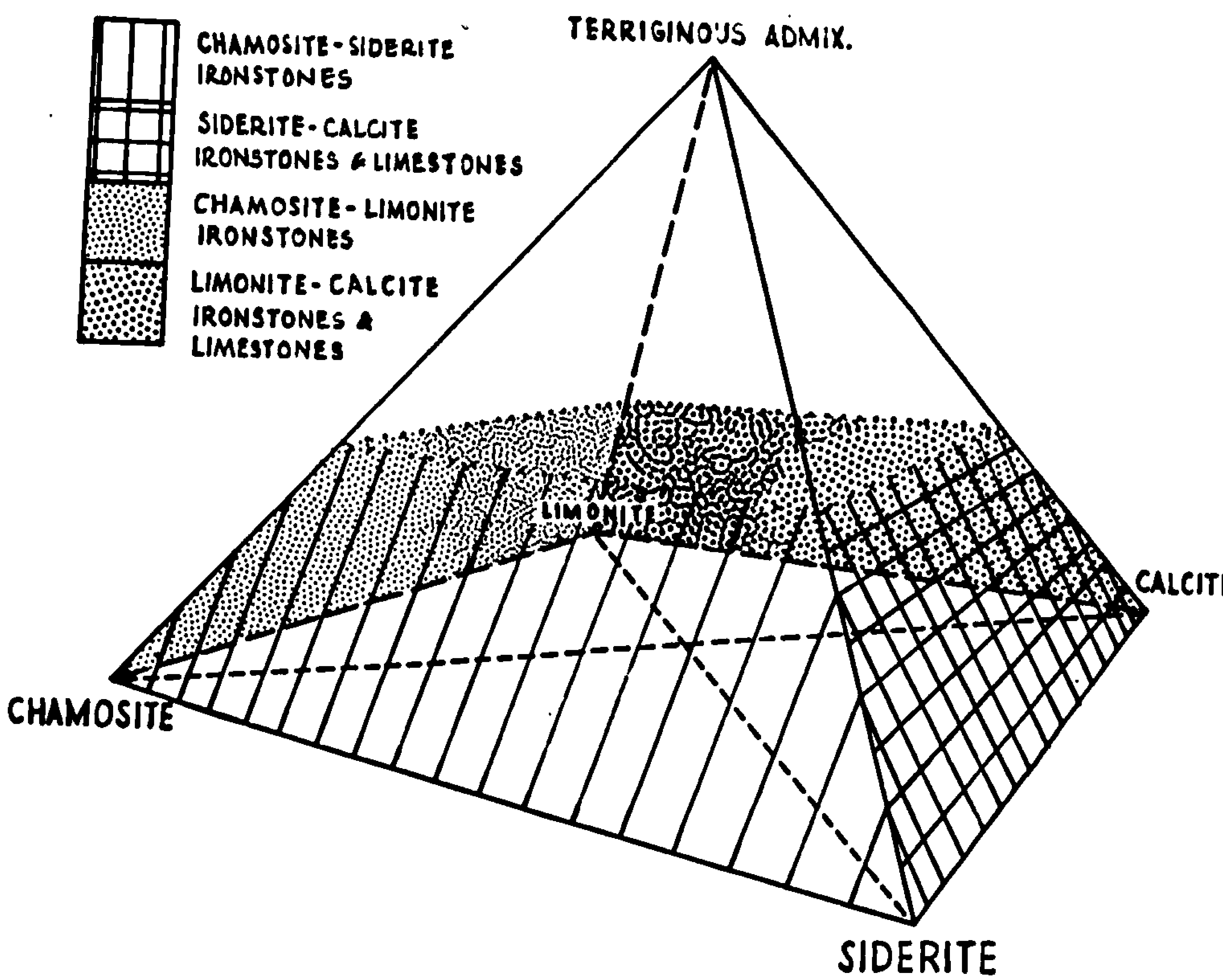


FIG. 28. TRIANGULAR DIAGRAM OF MINERALOGICAL FACIES.

and at its base the more important iron facies (oxide, silicate carbonate) together with calcite (fig. 28). In the figure the most common associations are given by the sides of the pyramid, the less common types by planes through the diagonals drawn upon the base.

2. Mineralogical facies of the Cleveland Ironstone Seams

In these ironstones the dominant iron minerals are siderite and chamosite. Pyrite occurs fairly commonly but in small amounts (except in the Sulphur Band) while limonite is uncommon except as a product of recent weathering. Each seam mainly comprises a two phase association between carbonate and silicate, although single phase horizons are known.

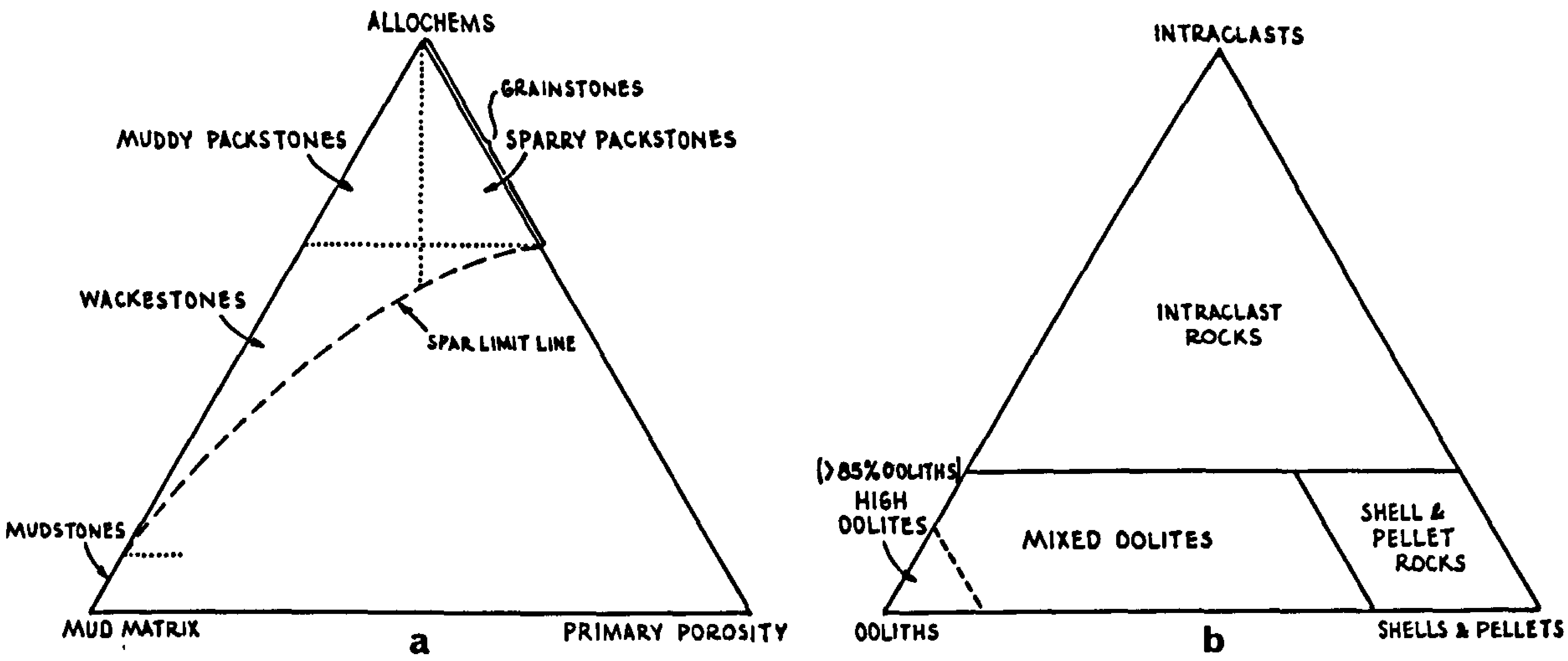
The greater part of the gangue within the ores, and that which exerted the major control on their workability, is accounted for by clay and silt size terriginous clastics.

The Cleveland Ironstones therefore fall within the broad field of the silicate-carbonate ironstones.

B. CLASSIFICATION BY TEXTURE

1. General

Although bedded sedimentary ironstones belong to that group of sediments known as chemical or non-clastic, in common with limestones they are conspicuously clastic textured in consequence of their mechanical deposition. The main disadvantage of a mineralogical



FOLK-DUNHAM LIMESTONE CLASSIFICATION

VOLUMETRIC ALLOCHEM COMPOSITION	GRAIN SUPPORTED			MUD SUPPORTED		
	MUD FREE	MUD < SPAR	MUD > SPAR	> 10% ALLOCHEMS	1%-10% ALLOCHEMS	< 1% ALLOCHEMS
	GRAINSTONES	PACKSTONES		ALLOCHEMICAL MUDSTONES (WACKESTONES)	MUDSTONES	
> 25% INTRACLASTS	INTRACLAST GRAINSTONE	SPARRY INTRACLAST PACKSTONE	MUDDY INTRACLAST PACKSTONE	INTRACLAST WACKESTONE	MOST ABUNDANT ALLOCHEM: INTRACLAST MUDSTONE	MUDSTONE
< 25% INTRACLASTS; > 25% OOLITHS	OOLITH GRAINSTONE	SPARRY OOLITH PACKSTONE	MUDDY OOLITH PACKSTONE	OOLITH WACKESTONE	OOLITE MUDSTONE	
< 25% INTRACLASTS; < 25% OOLITHS; VOLUME RATIO PELLETS : SHELLS > 3:1	PELLET GRAINSTONE	SPARRY PELLET PACKSTONE	MUDDY PELLET PACKSTONE	PELLET WACKESTONE	PELLET MUDSTONE	
VOLUME RATIO PELLETS : SHELLS 1:3-3:1	SHELL PELLET GRAINSTONE	SPARRY SHELL PELLET PACKSTONE	MUDDY SHELL PELLET PACKSTONE	SHELL PELLET WACKESTONE		
VOLUME RATIO PELLETS : SHELLS < 1:3	SHELL GRAINSTONE	SPARRY SHELL PACKSTONE	MUDDY SHELL PACKSTONE	SHELL WACKESTONE	SHELL MUDSTONE	
	TYPE I		TYPE II		TYPE III	

c

FIG. 29.

Types of spar not related to primary porosity are treated separately and not used in the classification applied here.

3. Textural classes (after Durham 1962)

The most important distinction made by Dunham (1962) is between grain-supported rocks, in which the grains are in point contact, and mud-supported rocks in which they are floating. This separation is more meaningful than an arbitary division of a textural field based on grain abundance, since it allows for the effect of grain shape upon packing. However, it is possible to qualify the division between mud and grain-supported fabrics for different grain facies, enabling a comparison of packing equivalents to be made. The difficulty of differentiating between grain and mud-support is overcome after some experience of grain-support in mud-free rocks.

Two divisions of grain supported rocks are recognised by Dunham, grainstones and packstones, and also two mud-supported divisions, wackestones and mudstones. A fifth type in which the constituents were bound together during deposition is known as boundstone, but is unlikely to be of importance amongst ironstones.

a) Grainstone was used by Dunham for mud free carbonate rocks (mud $<$ 1%). It finds no exact equivalent in Folk's scheme but includes the most cleanly washed sparites (type I).

b) Packstone denotes a grain-supported rock in which intragranular mud is present. In the present terminology two types are recognised, sparry packstones (spar $>$ mud) and muddy packstones, to coincide approximately with Folk's (1959) sparites (type I) and grain rich allochemical micrites (type II pars.).

c) Wackestones are mud-supported rocks containing more than 10 per cent allochems. As with the packstones two types are possible, but in practice sparry allochemical mudstones are probably rare. The wackestones are not completely analogous with Folk's allochemical micrites (type II) but occupy that part of the field left by the muddy packstones.

d) Mudstones are designated by a grain content of less than 10 per cent and are therefore identical to Folk's type III limestones (micrites and dismicrites).

4. Diagrammatic representation of textural fields

Textural variation may be conveniently represented by a triangular diagram upon which the percentages of grains, matrix and pore-space are plotted. In practice, however, allochems are plotted with mud matrix and sparry cement, for limestones and ironstones (fig.29a). The relative fields for each textural class are given in the same figure. It will be seen that the size of each field is dependent upon the positions of three boundaries: the grain limit, spar limit and grain framework limit.

a) A <u>grain limit</u> exists because there is an absolute maximum tightness with which any association of grains may be packed without deformation.

b) The <u>spar limit</u> is dependent upon the interelationship between grains, mud and spar, but appears to be primarily related to the grain percentage.

c) The <u>grain framework limit</u> defines the minimum grain percentage capable of providing grain-support in a rock and is used in the separation of packstones and allochemical mudstones. Its position varies with grain shape and packing and is best estimated subjectively (Dunham 1962) although it may be approximated from the intersection of the spar limit with the grain to spar join.

5. <u>Subdivision of the main textural types</u>

The grain framework of an ironstone is provided mainly by allochems and to a lesser extent by terriginous material. Following Folk (1959, 1962) the subdivision of the major textural types is accomplished on the basis of allochem content. Four fundamental allochem types are utilised for this subdivision and listed below in order of importance as environmental indicators.

a) <u>Intraclasts</u> (clasts of contemporaneously reworked sediment of local derivation), because they indicate erosion with its implications, are considered most important and hence a rock with more than 25% of the allochems intraclasts is called <u>intraclastic</u>.

b) Ooliths (coated grains) are also important environmental indicators and designate a rock oolitic when present in excess of 25% of the allochems, provided there are less than 25% intraclasts. Note that the whole spectrum of oolith-rich deposits are referred to loosely as oolites.

c) Pellets (rounded, spherical to ellipsoidal aggregates of clay sized particles, devoid of internal structure, thought, in the main, to be of faecal origin).

d) Shells (skeletal grains). When a rock contains less than 25% intraclasts and less than 25% ooliths the name assigned to it depends upon the relative proportions of shells and pellets (fig. 29c).

On the basis of modal analyses the percentage of each allochem in a rock may be plotted upon the triangular diagram illustrated in figure 29b . Although Folk (1959, 1962) plots pellets together with shells, some authors prefer to include them with the intraclasts. (e.g. Stauffer 1962, Imbrie and Purdy 1962). In the Cleveland ironstones the difficulty of separating pellets from matrix has necessitated that they be counted with mud.

6. Rock names

Figure 29c summarises the textural classification and its subdivision, outlined in the foregoing paragraphs, and names the range of textural types liable to be encountered amongst sedimentary iron-ores and associated chemical sediments. For more detailed subdivision Folk emphasises the use of informal qualifications (1959, p. 20, 1962? p. 72-83). A large number of useful modifiers might be applied to the wide variety of ironstone types but care must be taken to avoid overloading the terminology. Two modifiers have been selected below.

a) <u>Terriginous admixture</u>

In the passage from chemical sediment into terriginous sediment, allochems give place to detrital sand and silt grains, and an orthochemical mud passes into a terriginous mud, giving rise to a variety of sandy, silty and shaly ironstone types. ~~as illustrated in figure~~

b) <u>Mineralogy</u>

Use is made of adjectival and substantival prefixes in the qualification of primary and secondary minerals in the grains, matrix and cement, but without the connotation of Taylor's prefixes (1949, p. 5). The rock names are set out as follows:-

GRAIN MINERALOGY (noun)	GRAIN TYPE (adjective)	MATRIX MINERALOGY (noun)	CEMENT MINERALOGY (adjective)	TEXTURAL CLASS (noun)
chamosite-	oolitic	chamosite-	sideritic	packstone

Examples:-

(i) limonite-oolitic, calcitic grainstone.

(ii) intraclastic, limonite-oolitic, chamosite-sideritic packstone.

(iii) chamosite-oolitic, shelly, siderite-chamosite wackestone.
(siderite > chamosite).

(iv) chamosite-pelletal, chamosite-siderite wackestone.
(chamosite > siderite).

(v) chamosite siderite mudstone.
(ratio of siderite mud : chamosite mud $> {}^{2}/_{3}$).

A nomenclature of this type provides a useful means of describing individual rock specimens, but is unnecessary for general use. For the latter the nomenclature should be adapted in order to bring out the most significant variations.

III CONSTITUENT GRAIN TYPES

A. OOLITIC GRAINS (COATED GRAINS)

1. Definitions

Ooliths (oolites, ooids) are spherical to ellipsoidal bodies of sand size built by the accretion of mineral material about a nucleus in order to produce a concentric and, or radial structure (Amer. Geol. Inst. 1962). Most commonly they are calcareous, but in ironstones they may be haematitic, limonitic, chamositic, etc. They give rise to a suite of oolitic rocks or oolites. (When these grains exceed 2 mm. in diameter they are known as pisoliths).

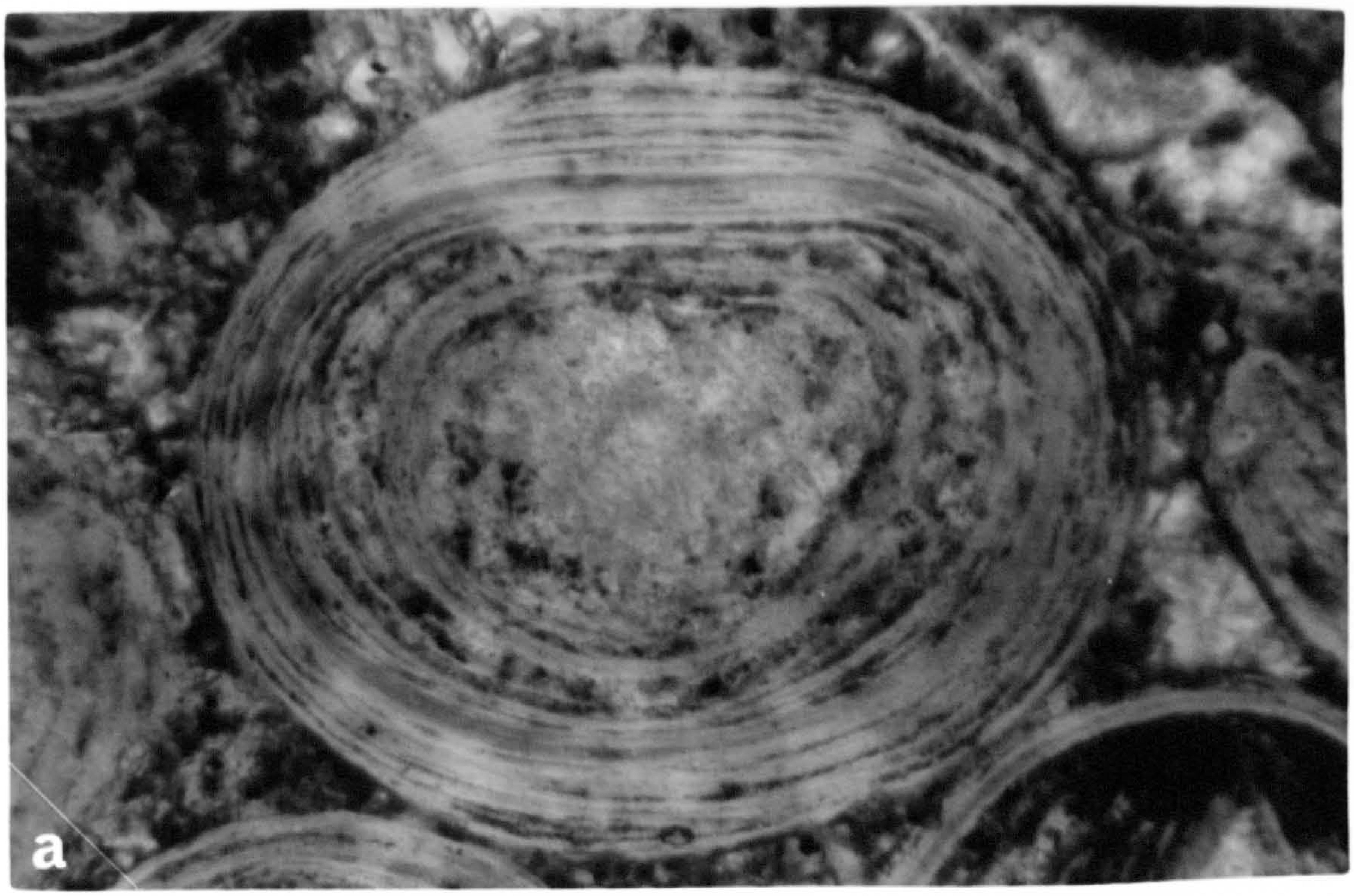
2. Structure

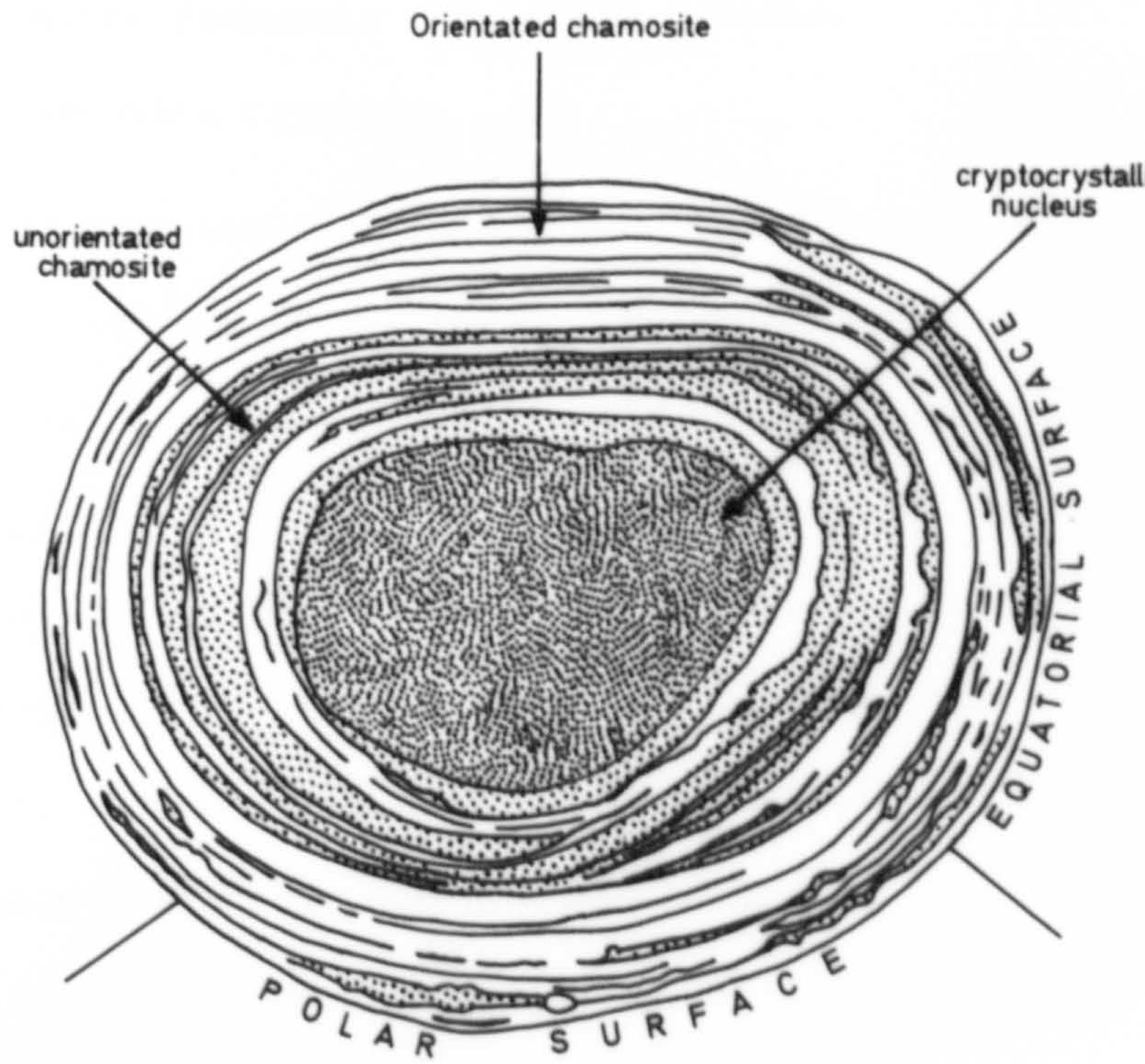
Ooliths are by far the most important grain type in the ironstones frequently accounting for 90 per cent or more of the grain framework. They are made dominantly of chamosite, apparently of synsedimentary origin, other minerals being either impurities or resulting from replacement during diagenesis. A concentric type structure is the result of inhomogeneities between the chamosite laminae, which form the oolitic envelope around the nucleus, (plate) 4). The relative importance of the envelope varies; from being superficial in superficial ooliths (Illing1954), to well developed in normal concentric ooliths.

PLATE 4 Internal microstructure of typical oolith from Main Seam, North Skelton

a) Thin section ~~x1000.~~ x200

b) Explanatory diagram.


a


Orientated chamosite
cryptocrystalline nucleus
unorientated chamosite
EQUATORIAL SURFACE
POLAR SURFACE

b

PLATE 4

3. Nuclei

The presence of a nucleus, however small, would appear axiomatic to the formation of ooliths by accretion, although this nucleus may be difficult to differentiate in thin section, either because it lies outside the plane of section or because it has been obscured by diagenesis. It is only in the relatively unaltered rocks that it is possible to identify the nuclei consistently. They are of four main types.

(i) Cryptocrystalline chamosite mud.

(ii) Shale and mudstone intraclasts.

(iii) Oölite fragments and broken ooliths.

(iv) Chamosite crystals.

Other types such as shell fragments and quartz grains only account for a small proportion of the total. The most important nuclei are therefore all derived from within the basin of deposition.

a) Cryptocrystalline chamosite mud constitutes the most common nucleus for ooliths from the Main Seam (70 percent) but is less common in the Two Foot and Raisdale Seams. It also forms the least distinctive of all nuclei. The mud is structureless, pseudoisotropic and quite indistinguishable from the unorientated chamosite of the envelope in its grey-olive, grey-olive-brown and grey-brown colours (page 110).

PLATE 5 Ooliths with nuclei of varying types,

Main Seam, North Skelton.

a) Ordinary light.

b) Crossed polars ~~x500.~~ x100

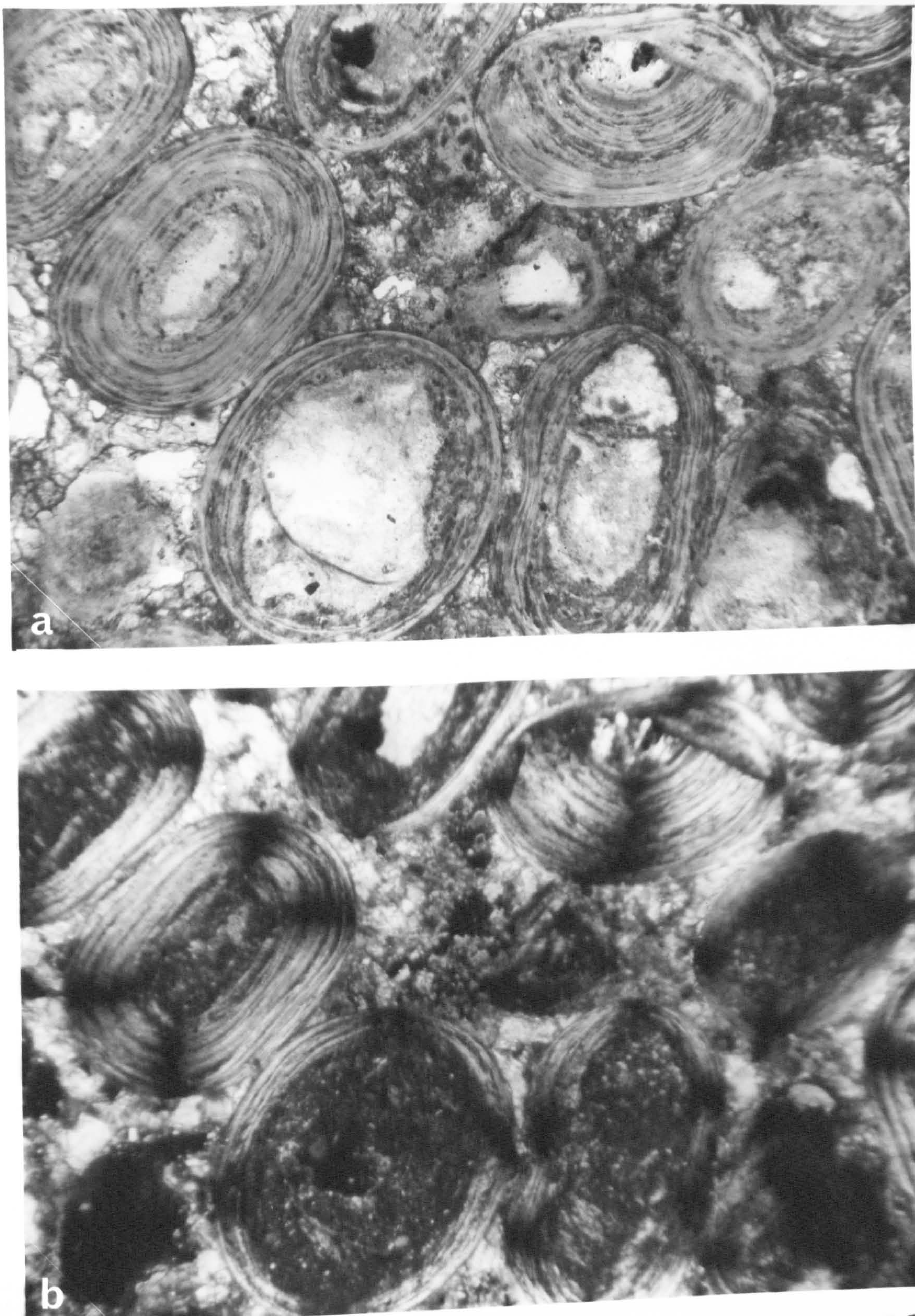


PLATE 5

In consequence the nucleus usually grades imperceptibly into the envelope, and the shape although apparently well rounded, is poorly defined (plate 4).

In all probability these nuclei originated as faecal pellets, but it is impossible to be dogmatic. Faecal pellets have been shown to play an important part in the nucleation of modern calcareous ooliths (Purdy 1963, p. 3&6), and are known to occur in association with ooliths in a number of ironstone facies (pages 130-132).

b) Shale and mudstone intraclasts may be distinguished by their colour, shape and internal structure (plate 5a). The colour often contrasts with the olive shades of the oolitic envelope, usually being grey to grey-brown and brown. In part the brown colouration is the result of phosphatisation before the intraclast became incorporated in the oolith (page 129) and in part it is the result of preferential iron staining subsequent to deposition, probably as a result of weathering. A characteristic lack of rounding and low sphericity is often sufficient for the recognition of an intraclast even where its internal structure is obscure. Owing to the fine grained nature of these grains and also to their partial phosphatisation they may appear almost isotropic, but in some the internal structure is preserved by included detritus such as silt sized mica flakes and quartz.

c) Oolite fragments and broken ooliths are distinctive because of the discontinuity between the oolitic envelopes in guest and host grain. Where a broken oolith is the nucleus there is little colour difference between the two, so that breakage appears as an unimportant interruption to the development of a normal oolith (plate 5a). Such nuclei are not therefore truly intraclastic. However, some broken ooliths and all oolite fragments are derived by erosion of consolidated and semi-consolidated ironstones and may have suffered replacement, particularly by siderite before incorporation in their present host.

d) Chamosite crystals of fine to medium sand size may account for up to 60 per cent of the nuclei in ooliths from the Two Foot and Raisdale Seams. They are the most distinctive of the types so far described (plate 6) and are often discernable even where ooliths have suffered heavy alteration. The colour varies between olive-green and light brown in thin section with slight pleochroism (greatest adsorption for rays vibrating parallel to the cleavage). The perfect basal cleavage is one of the most prominent characteristics of these flakes. In polarised light they are anisotropic up to first order yellows; slightly higher than the chamosite in the oolitic envelopes. Since the crystals are frequently elongated along the oolith equator, the c-axis commonly lies through the poles, although it may pass through the equator (plate 6b). Intermediate positions, however, are rare.

PLATE 6 Oolith nuclei:

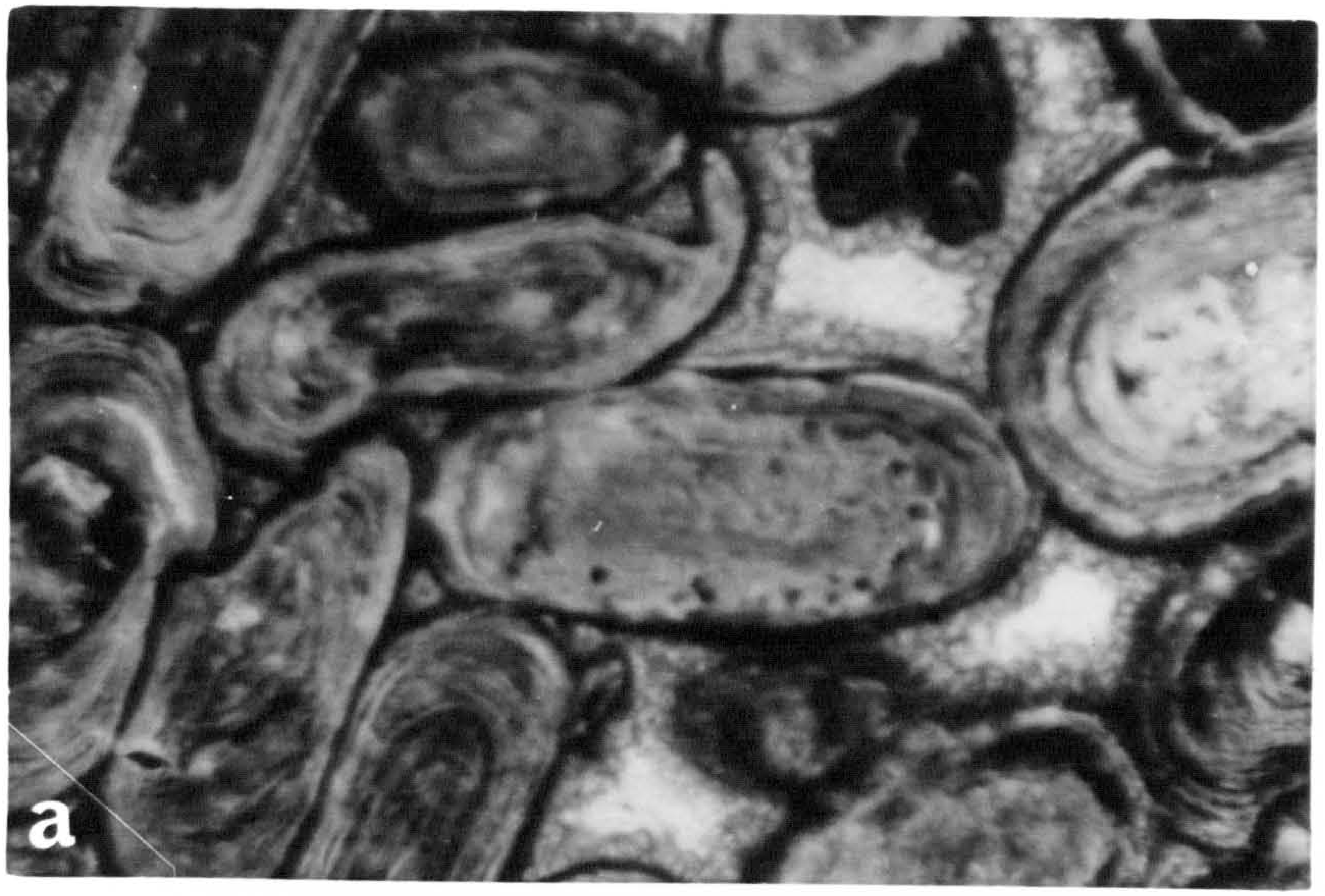
a) Bored shell fragment: Two Foot Seam, Ayton Mine. x100

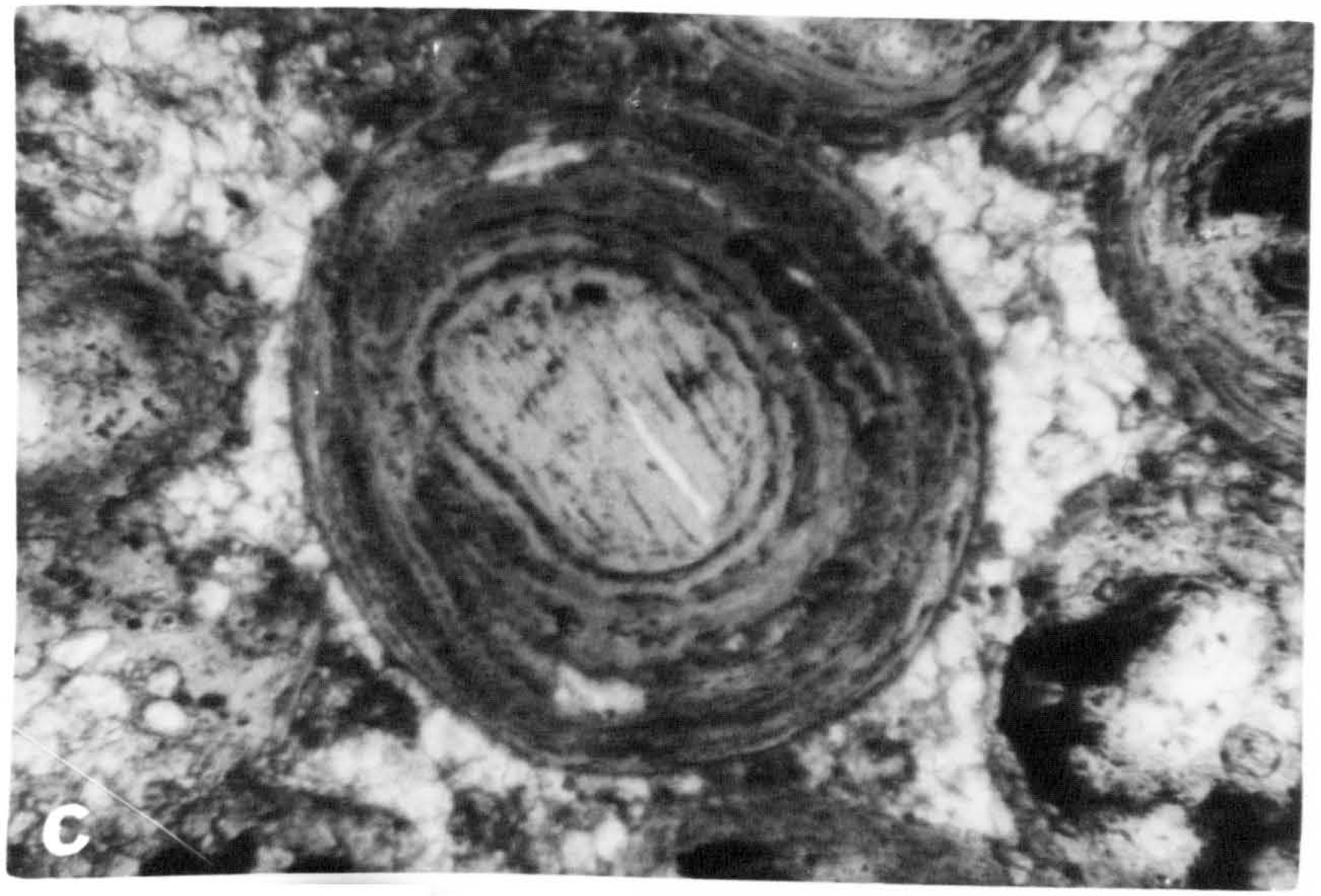
b) Chamosite flakes: Two Foot Seam, Skelton Beck. x70

c) Rounded chamosite flake: Main Seam, North Skelton. x100

d) Contracted chamosite flake: Raisdale Seam, Harton Gill. x70

~~x 300.~~





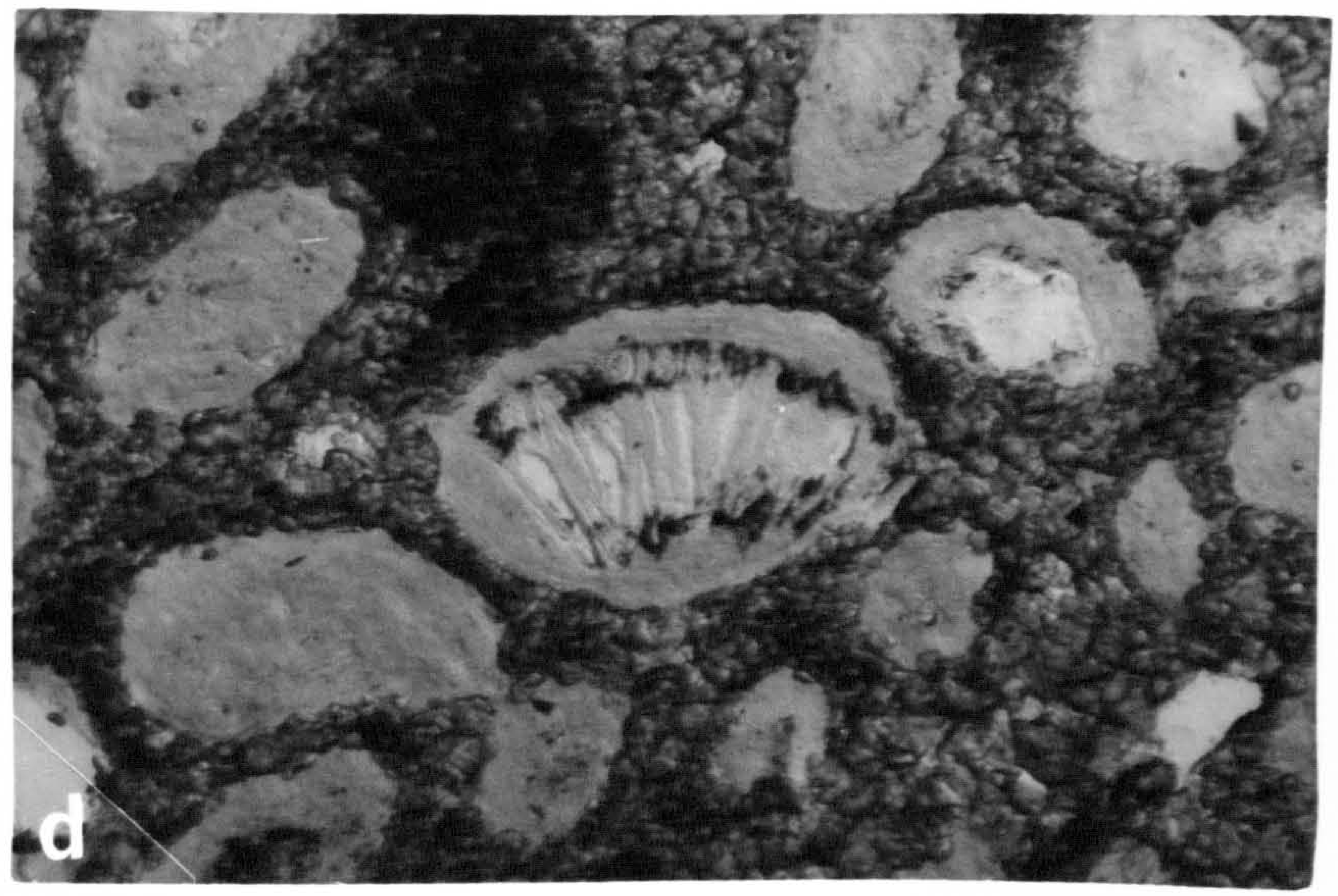


PLATE 6

Although these grains are probably authigenic in origin (pages 194-195) several facts indicate that they are derived from outside the ooliths. They are usually rounded and abraded, and fail to interrupt the laminations of the oolitic envelope, which conform to any irregularities. The orientation of the flakes is not explicable in terms of authigenic growth within the oolith (Pattinson 1964), but is similar to that of intraclasts. While the present evidence favours a detrital origin, therefore, it is probable that such crystals form a favourable site for chamosite recrystallisation. Certain crystals from the <u>Avicula</u> and Raisdale Seams appear to have been enlarged in this way (page 194).

e) <u>Other types</u>

Quartz grains are a rare occurrence in the oolitic facies of the ironstones even as the nuclei of ooliths, although very occasional well rounded grains do occur. Shell fragments are less rare especially in the Two Foot Seam. They may usually be identified by shape as well as mineralogy. This is important because some have been converted into yellow-green chamosite, in which case they could be confused with mudstone intraclasts (plate 6a).

4. Normal concentric envelopes

A variety of different types of oolitic envelope are described in the literature and are probably attributable to different modes of origin; for example some form by replacement, while others are biochemically (algal envelopes) or physicochemically (sprüdelstein envelopes) deposited from solution. (Twenhøfel 1932, 1961, 757-769). The envelopes in the present ooliths are almost exclusively of normal concentric type, built up of concentrically laminated and layered chamosite, analagous with the aragonite of recent ooliths (Newell et al 1960, Rusnak 1960) (plate 5a)

Petrologically the chamosite within the envelopes is of two kinds. In the first there is a preferred orientation amongst the component crystals, which is responsible for the pseudo-uniaxial negative cross produced under polarised light, while in the second the crystals are unorientated and appear pseudo-isotropic (plate 5b). The variability in the definition of these polarisation effects suggests that every transition exists between strongly orientated and completely unorientated chamosite.

a) Orientated chamosite

The orientated crystals are built into delicate laminations of clear olive-green to brown colour, which form the most conspicuous part of the envelope. Since the crystals are disposed with their c-axes radial to the nucleus, the surface of each lamina, under

PLATE 7

a) Hand sorted ooliths, Main Seam, North Skelton. x 40.

b) Detail of oolitic envelope showing interlaminated orientated (light) and disorientated (dark) chamosite. x300 ~~÷ 1500.~~

c) Tangential view of oolith lamina consisting of basal pinacoids of chamosite. Electron micrograph. X 9000

d) Transverse section of laminated chamosite. Electron micrograph. X 20,000

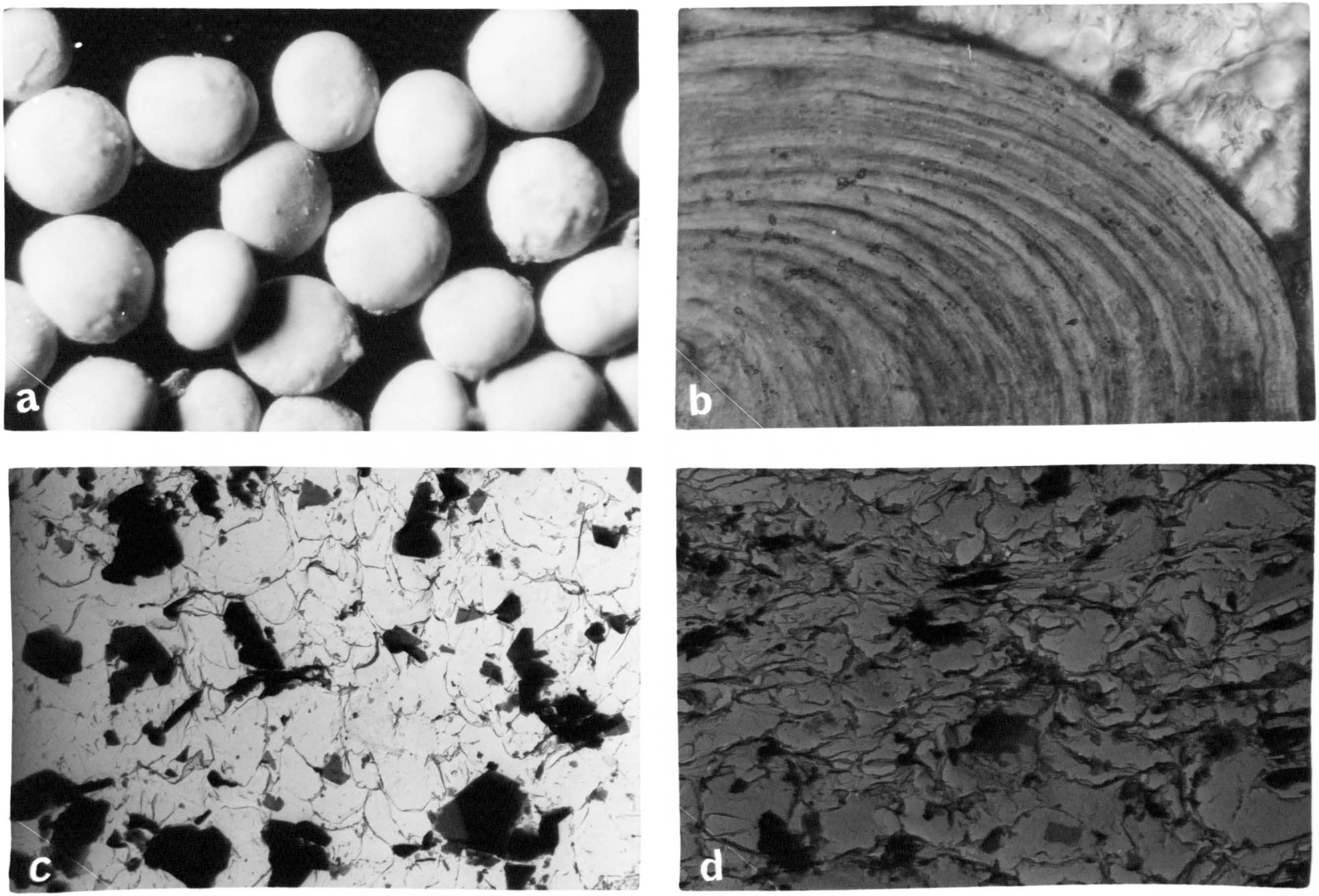


PLATE 7

the electron microscope, appears as a mozaic of basal pinacoid plates up to a maximum of about 5μ across (plate 7c). The individual laminae may reach a maximum thickness of about 4μ, although averaging perhaps 2μ, each probably characterised by a slightly different grain size, and degree of preferred orientation (plate 7d). Thicker layers upwards of 5μ, which may be visible in hand specimen, result from the superimposition of laminae of similar petrographic type. In a well developed laminated envelope, assuming an average laminae to be about 2μ in thickness the number of the latter might be expected to reach about 150. However, this number would be reduced depending upon the total thickness of the envelope and upon the presence of unorientated mineral, so that a more likely average would lie in the region of 50 - 100.

By polarised light these laminations stand out, depending upon the degree of preferred orientation, in weak first order birefrigence colours (greys and whites). The presence of higher colours is indicative of the enhanced preferred orientation produced by compaction (pages 162).

b) Unorientated chamosite

With the loss of preférred orientation the delicate laminations of the oolitic envelope break down and the chamosite eventually appears cryptocrystalline. In ordinary light the mineral gradually loses its clarity and changes colour (grey-olive, grey-olive-brown, grey-brown), probably due to a greater porosity, which renders it more susceptible to diagenetic alteration and staining ~~(page~~. It may occur in well defined layers or irregular lenses (plates 4 & 7b), but is more commonly interlaminated with, or passes laterally into orientated mineral, so that it is difficult to draw a sharp division between the two (plates 4 & 7b). Although in some layers unorientated chamosite appears not to disturb the continuity of the envelope, elsewhere the regular lamination is distorted (around lenses) or disrupted (in the thicker layers). The layers may be of variable thickness, but are particularly important in the early growth stages of certain envelopes. The lenses, on the other hand, are only developed in the outer parts of the envelope. Most importantly the distribution of unorientated chamosite within the envelope appears to have a bearing on the overall shape. The oblateness of ooliths from the Raisdale and Two Foot Seams, for instance, appears to depend upon the concentration of unorientated material about the equator (plate 8). Apparently this tendency is less marked in the Main Seam and the ooliths are correspondingly more spherical.

c) Causes of preferred and random orientation

Variations in crystal orientation analogous with those outlined above have been described from the envelopes of recent aragonite ooliths by Rusnak (1960) and by Newell et al (1960). According to the former acicular aragonite crystals may have several modes of occurrence in ooliths; in a radial orientation about the growing surface,, in a tangential orientation, or in unorientated aggregates. The occurrence of the first type is confirmed from the Great Salt Lake by Eardley (1938, p. 1375) and from the Laguna Madre, Texas by Rusnak (op. cit.) and Freeman (1962), and the latter two from Bahamian ooliths by Newell et al (op. cit.) and from the Laguna Madre by Rusnak (op. cit.). Excepting the mineralogical differences, the petrological descriptions given by these authors accord well with those on the previous pages. All are in agreement that normal concentric envelopes are the product of direct mineral precipitation upon the nucleus, from solution, in environments of high energy.

Rusnak (op. cit.) attributes the several modes of occurrence to variations in the rate of carbonate precipitation, and in the degree of mechanical abrasion. Thus radial growth might be initiated by slow precipitation and gentle agitation (Monaghan and Lytle 1956), while tangential growth could be assumed as a result of the distortion of the radial crystals during abrasion in more turbulent conditions. The unorientated crystals might then result where the development of preferred orientation was inhibited by the rapid dumping of precipitate. However, Freeman (1962) suggests that chemical changes in the environment, alone, may be responsible for the differences, while

Newell et al.(1960) suspect the intervention of encrusting algae in the unorientated layers and lenses.

Although the exact mechanisms by which these variations arise remain to be demonstrated in aragonite ooliths, similar variations exist in chamosite ooliths, and it seems fair to assume that the processes of formation were similar, (pages 300-302). The crystal habit of chamosite (a phyllosilicate) probably reduces the possible types of crystal arrangement to two, orientated (c-axis radial) and unorientated, by making the c-axis tangential orientation, so important in aragonite ooliths, redundant. Following the authors cited the orientated chamosite may be ascribed to physico-chemical deposition. In this eventuality the perfection of the preferred orientation might reflect the speed of precipitation, or the degree of mechanical abrasion. The latter it is inferred would tend to enhance the c-axis radial orientation in chamosite, where it distorts it in aragonite (Rusnak op.cit.). Similarly, the unorientated chamosite might originate physico-chemically, but the different types of occurrence suggest several different origins. The presence of this material in lenses recalls the theory of Newell et al. (1960), that unorientated crystals represent interstitial precipitation by algae. The disruption of orientated mineral in certain cases may be caused by boring algae. A further possibility, of penecontemporaneous recrystallisation, will be treated in more detail subsequently (page 194). It is conceivable that each of these processes has played a part in producing the mineral disorientation in the oolitic envelopes, but until more is known of modern aragonite envelopes it is impossible to be dogmatic. The explanation of these variations within the oolitic envelope raises the whole question of chamosite oolite formation, which is fundamental to the discussion of the origin of minette type ones. However, this problem is the subject of more detailed discussion in a later chapter.

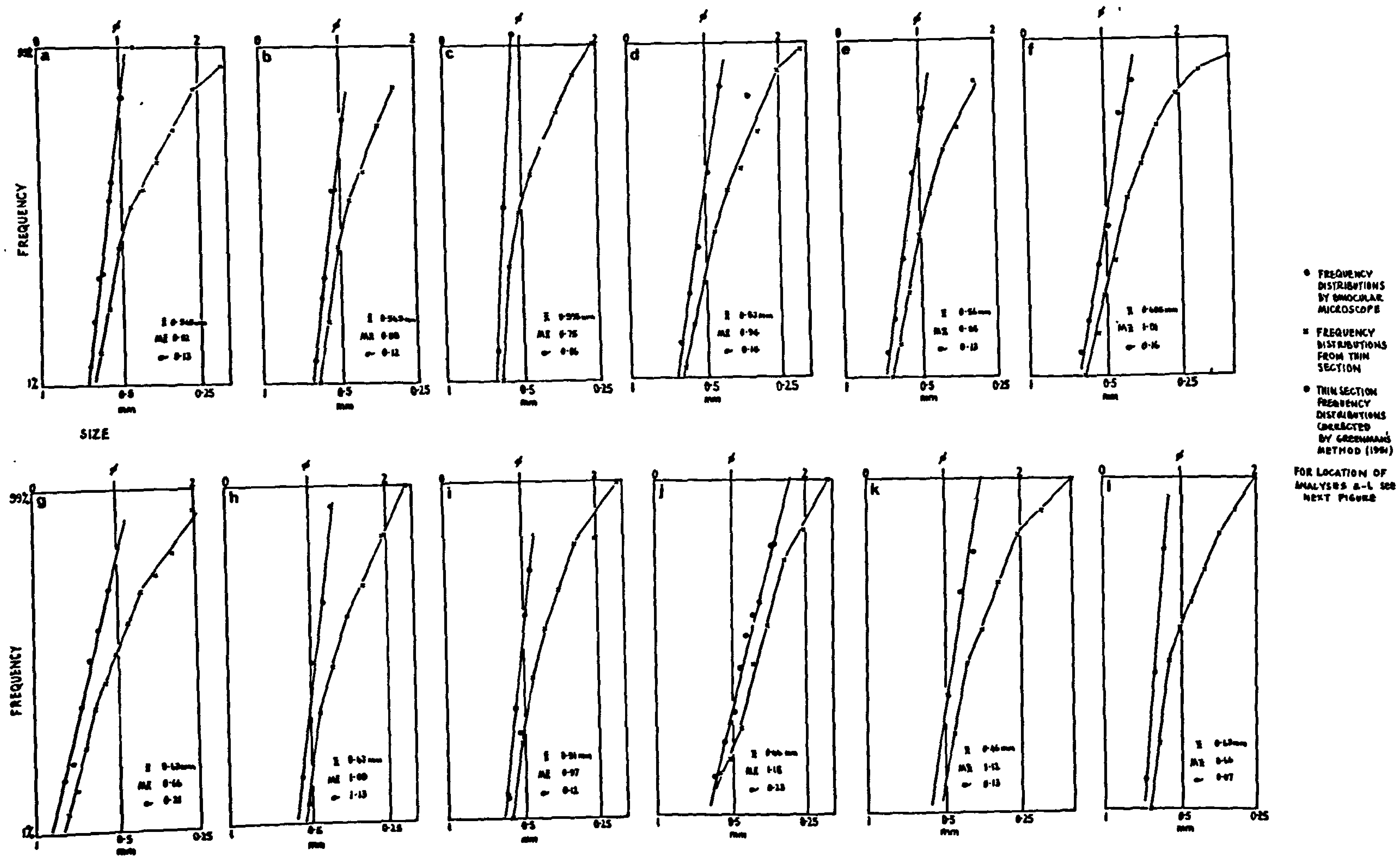
d) Interlamina sutures

The outer surfaces of normal ooliths, when they have been freed of matrix, are revealed as smooth, shiny and porcellanous (plate 7a). The disruption of an oolith with a pin provides a succession of such polished surfaces, which have been preserved within the oolitic envelope and which are seen in thin section as the interlamina sutures, the most prominent manifestation of the concentric structure in plane polarised light. They confirm the importance of intervals of mechanical abrasion in the accretionary process by which an oolitic envelope is formed, and once again find an exact analogue in recent aragonite ooliths.

5. Size, shape and roundness of normal ooliths

Normal concentric ooliths are notable for their geometrical properties: size, shape and roundness. Many authors have commented upon this fact, although little quantitative data, in the form of

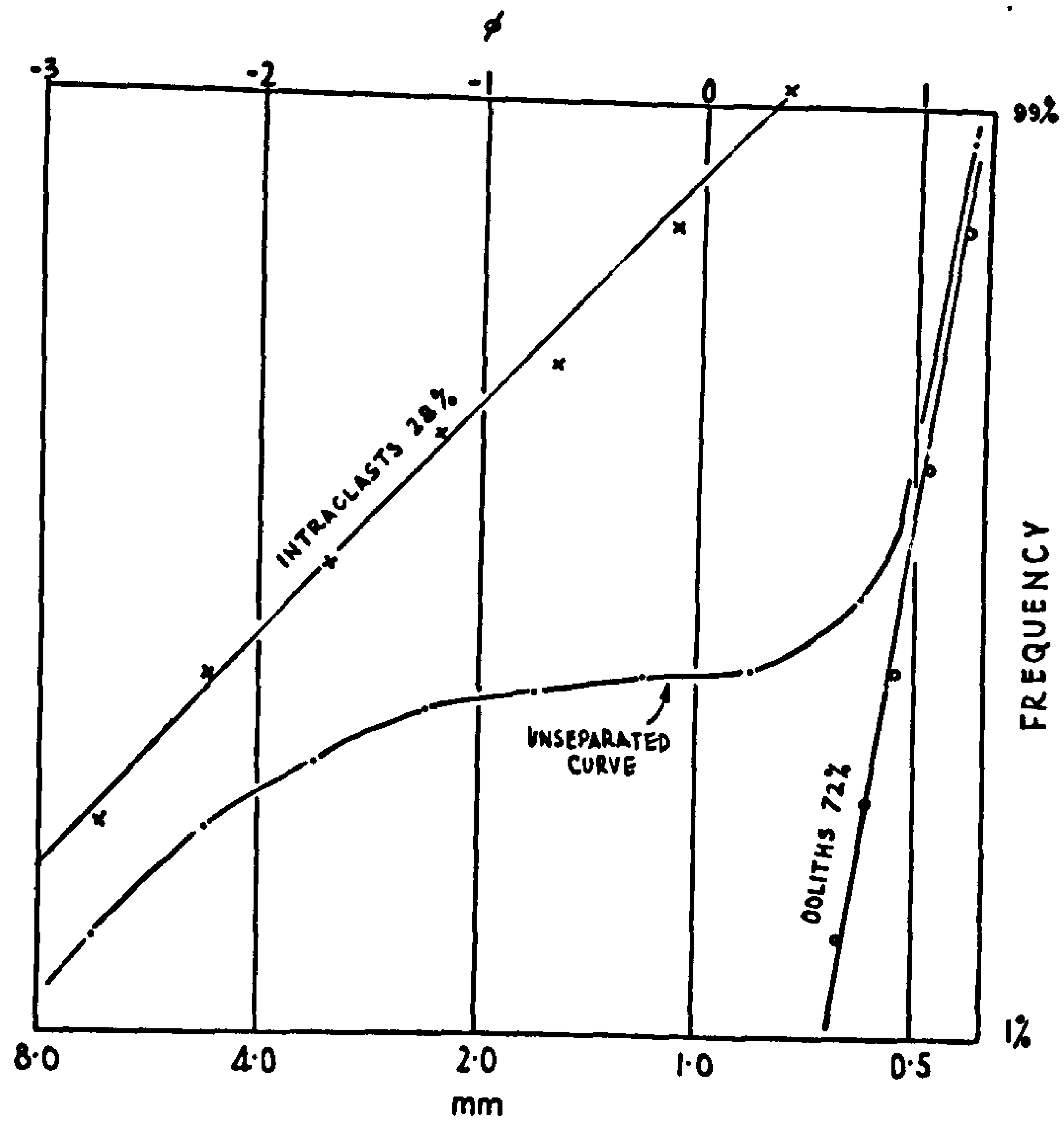
FIG. 30. SIZE FREQUENCY DISTRIBUTIONS.



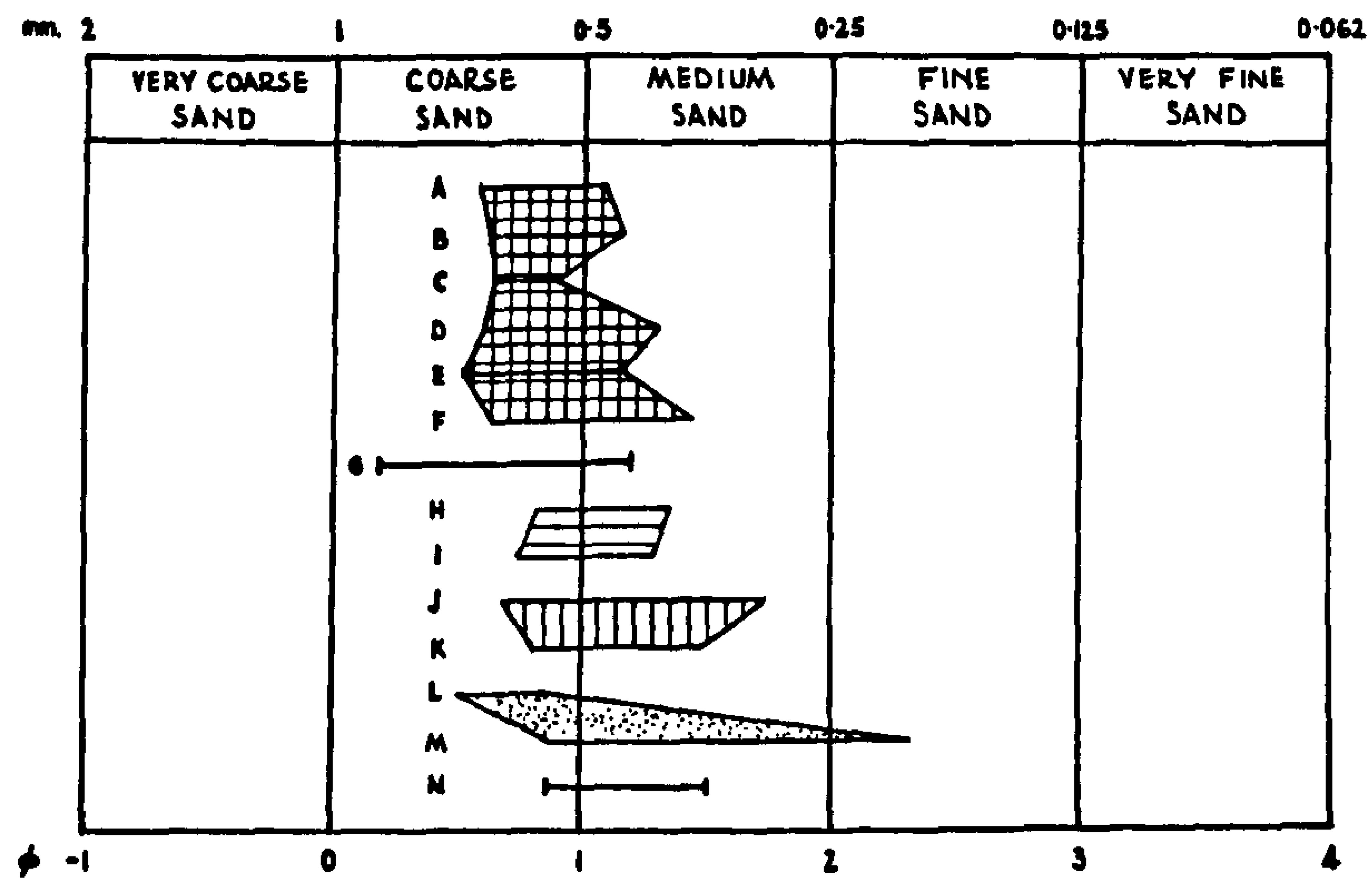
mechanical analyses, sphericity and roundness measurements, is available for ooliths. More particularly it is the general uniformity of size and shape within a given rock or deposit which has excited interest. In the present deposits it is possible to verify these observations, both qualitatively and quantitatively. Often the geometrical properties of the ooliths from different seams are sufficiently diagnostic to identify their seam of origin.

a) Size

Mechanical analyses were carried out from thin section and plotted on logarithmic probability paper. For the interpretation of this data it was found essential to apply a bias correction to eliminate sectioning effects. Several different corrections have been proposed, and are discussed at greater length in appendix but the method selected as most applicable to the present study was that of Greenman (1951). This method utilises long axis measurements made in thin section to provide converted long axis frequency distributions of the type prepared from loose grains. To test its accuracy corrected distributions were compared with loose grain measurements made under the binocular microscope and found to be in good agreement (appendix II). Corrected cumulative curves for sample slides from the Avicula, Raisdale, Two Foot, Pecten and Main Seams are given in figures 30 & 31 , and the statistical measures, mean and standard deviation in ~~table~~ fig 30 .



a SIZE FREQUENCY DISTRIBUTION FOR INTRACLASTIC IRONSTONE FROM MAIN SEAM SKELTON BECK 2' 0" FT WITH SEPARATED LINES FOR INTRACLASTS & OOLITHS



A MAIN SEAM TOP BLOCK STAITHES (111)
B MAIN SEAM TOP BLOCK LUMPSEY MINE (119)
C MAIN SEAM TOP BLOCK SKELTON BECK 1' 0" FT
D MAIN SEAM TOP BLOCK SKELTON BECK 2' 0" FT.
E MAIN SEAM TOP BLOCK NORTH SKELTON 2' 0" FT
F MAIN SEAM BOTTOM BLOCK NORTH SKELTON 7' 6" FT
G GROSMONT PECTEN UNIT HAWSKER (221)
H TWO FOOT SEAM STAITHES (104)
I TWO FOOT SEAM AYTON MINE (261)
J RAISDALE SEAM HARTON GILL (264)
K RAISDALE SEAM SCUGDALE (270)
L AVICULA SEAM STAITHES (101)
M AVICULA SEAM GROSMONT (276)
N OSMOTHERLEY SEAM HAWSKER (283)

b RANGE IN SIZE OF OOLITHS FROM THE CLEVELAND IRONSTONES

FIG. 31.

The overall size ranges (maximal and minimal sizes) have been approximated at the 1 and 99 percentiles and together with the range of means, are summarised in figure. 31b. It should be stressed that these results are not directly comparable with those derived by sieving, each distribution being displaced in the coarse direction. From figure 31a it is apparent that the presence of oolitic envelopes is restricted to grains of fine to coarse sand grade. The maximal size observed (Carozzi 1960) was 0.88 mm. from the Pecten Seam at Hawsker (mean 0.63 mm.), although intraclasts from the Main Seam, in the very coarse sand grade and above, may occasionally be oolitised; but in these cases the envelopes are never entire (see pages 127-130). Among the smallest ooliths observed are some from the top block of the Avicula Seam at Rockcliff and Grosmont with a minimal size of about 0.2 mm. (mean 0.35 mm.). However, minimal values are difficult to determine in thin section.

Oolith grain size is less diagnostic of the different seams than oolith shape, being on the whole more variable, but may be utilised to some extent for their differentiation. Thus the maximal sizes from the Main and Pecten Seams exceed those from the Two Foot, Raisdale and Osmotherley Seams. As a general guide ooliths with long axes in excess of 0.60 mm. are rare in the Two Foot, Raisdale and Osmotherley Seams, but common in the Main and Pecten Seams

(i) Sample means were estimated graphically using Inman's (1952) formula $M\phi = (\phi 84 + \phi 16)/2$,

which is satisfactory for nearly normal curves of the present type (Folk and Ward 1957, p. 12). The overall range in the samples was between $\bar{x}$0.35 mm. (estimated from the *Avicula* Seam) and $\bar{x}$0.63 mm. (from the *Pecten* Seam). In the Main Seam samples ranged from $\bar{x}$0.495 mm. to $\bar{x}$0.595, while in the finer grained Two Foot and Raisdale Seams between $\bar{x}$0.44 mm. and $\bar{x}$0.51 mm. Although insufficient data is available to be specific about these ranges the conclusion that they are small is justified from observation, especially in the more oolitic facies (grainstones and packstones).

(ii) The phi standard deviation (Inman 1952)

$$\sigma = (\phi 84 - \phi 16)/2,$$

has been used as an adequate measure of sorting (Folk and Ward 1957, 13). All the samples fall under the description "very well sorted" (used by Folk and Ward (loc. cit.) for values under 0.35), with an observed range of between σ 0·30 (estimated from the *Avicula* Seam) and σ 0.06 from the Main Seam. The smallest σ value encountered by Folk and Ward (loc. cit.) from hundreds of analyses of modern sands was σ 0.20. By this standard the degree of sorting among the ooliths is remarkable, and probably the most important attribute of the frequency distributions.

PLATE 8 Oolith shape

a) Ellipsoidal ooliths. Main Seam, North Skelton.

b) Discoidal ooliths. Two Foot Seam, Ayton Mines.

c) Highly discoidal ooliths. Raisdale Seam, Scugdale.

d) Sub-ellipsoidal ooliths. Avicula Seam, Staithes.

~~x 280.~~
x 90

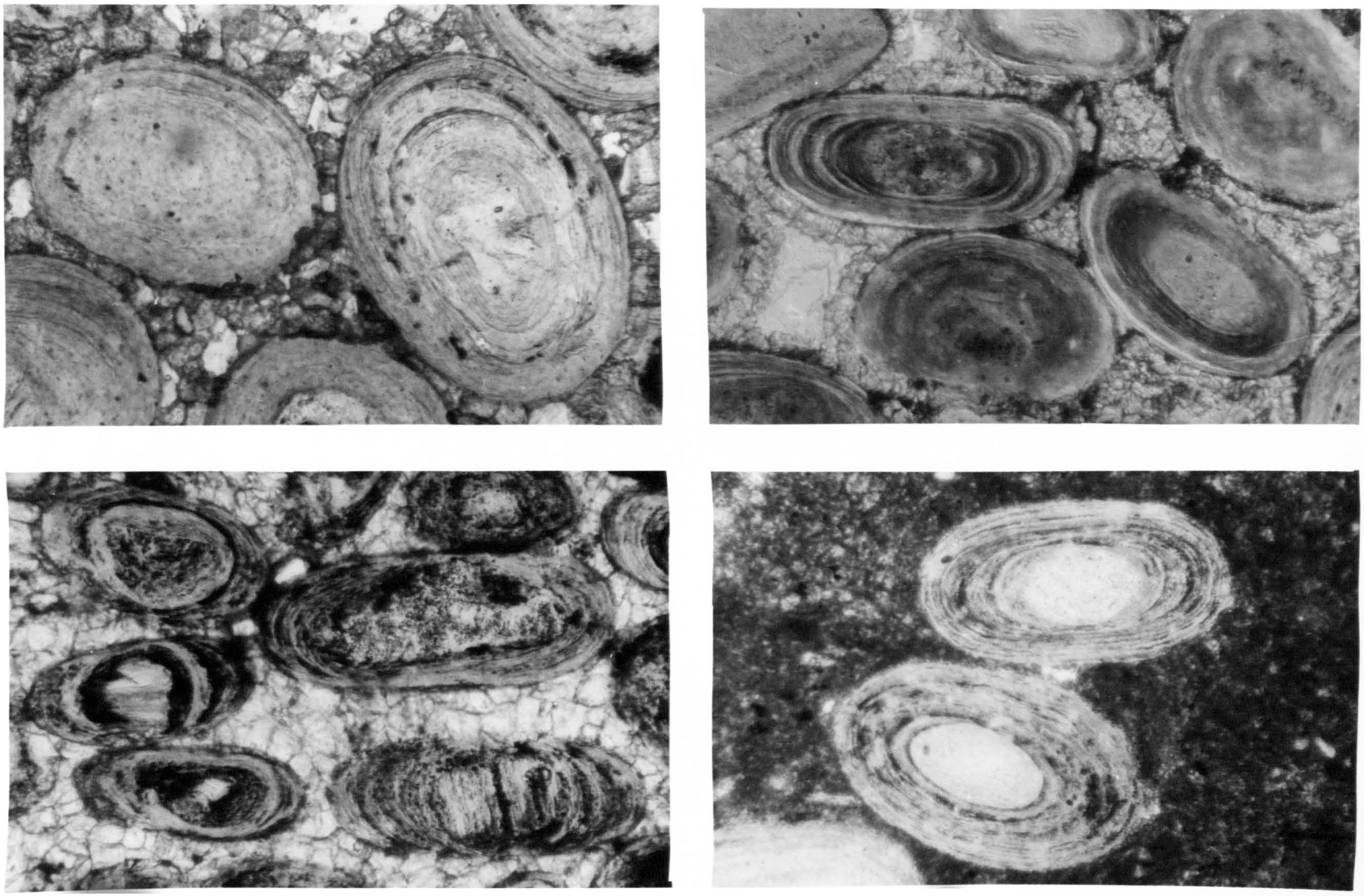


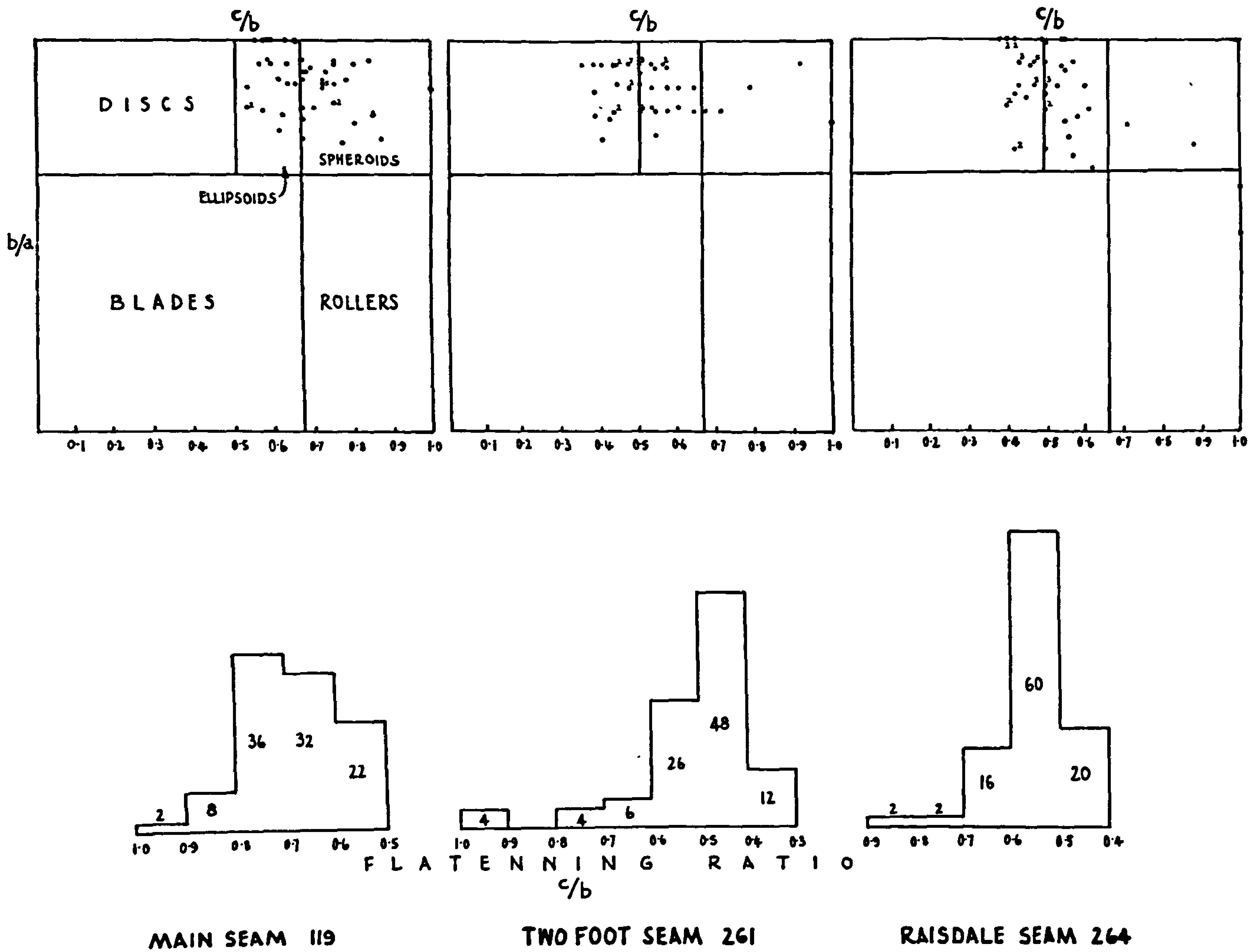
PLATE 8

(iii) Skewness and Kurtosis are important tests of the normalcy of the cumulative curve and the most sensitive environmental indicators. From an inspection of figure 30 it may be seen that all the curves approximate fairly closely to log normal, although some minor discrepancies exist. Unfortunately the data available is not sufficiently discriminating to indicate the significance, if any, of these minor variations. However, the approximation is close enough to reveal the essential unimodal nature of the distributions; nonskewed and with Kurtosis close to one.

b) Shape

Characteristically normal ooliths from the present ironstones are oblately ellipsoidal in shape. Overall they vary between oblate spheroids and discs, with some prolate spheroids, but with only rare roller and blade shapes (Zingg 1935). The type of variation involved is illustrated by plates 8 a-d and by the shape charts prepared for data from the Main, Two Foot and Raisdale Seams (figure 32). In equatorial section the majority of ooliths are subcircular, while in polar section, the section which is approximated most frequently in thin sections cut normal to the bedding, they appear flattened to varying degrees (plates 8). The complementary sphericities for these examples ~~are~~ were cumulated on arithmetic probability paper ~~in figure . They~~ and appear to be normally

FIG. 32.


c/b
DISCS
SPHEROIDS
ELLIPSOIDS
b/a
BLADES
ROLLERS
0·1 0·2 0·3 0·4 0·5 0·6 0·7 0·8 0·9 1·0
2 8 36 32 22
4 4 6 26 48 12
2 2 16 60 20
FLATENNING RATIO
c/b
MAIN SEAM 119
TWO FOOT SEAM 261
RAISDALE SEAM 264

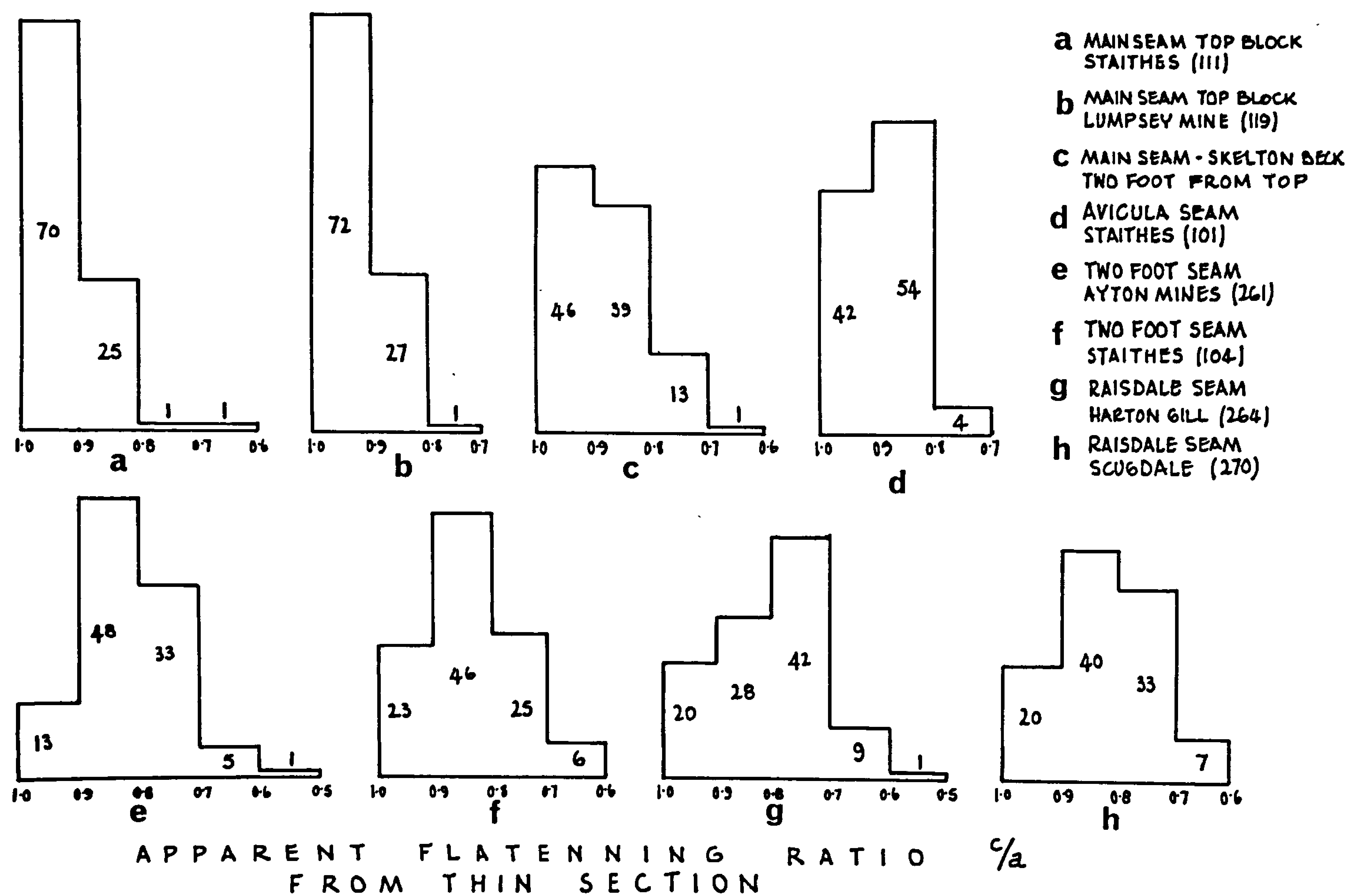
distributed and well shape sorted.

Shape varies from seam to seam and from sample to sample, but one of the most notable features which emerges from a comparison of thin sections is the preference of some seams for one particular shape. Thin sections are somewhat misleading for the study of shape but they provide apparent long and short axes values which can be of use for comparison (see figure 33).

For the purpose of description the ooliths may be ascribed to two different shapes. The first groups will be described as ellipsoidal, the second as discoidal. Figures 32 & 33 and plates 8a, d illustrate ellipsoidal ooliths from the Main and *Avicula* Seams. The modal shape in these examples lies close to the spheroid/disc boundary (flattening ratio $^{c}/_{b}$ about 0.75), which represents the highest modal sphericity attained. The majority of ooliths from the Main Seam belong to this type, although there is a certain amount of variation from sample to sample. Ellipsoidal ooliths also occur in the *Pecten* and *Avicula* Seams but only rarely in the other seams.

Most commonly ooliths from the Two Foot, Raisdale, and probably from the Osmotherley Seam also, are discoidal with a modal flattening ratio of about 0.45 (figures 32 & 33 and plates 8c, b). The most discoidal ooliths observed have a flattening ratio of about 0.3, equivalent to a maximal flattening ($^{c}/_{a}$) of about 1:3 as observed in thin section.

FIG. 33.


70
25
1
1
1·0
0·9
0·8
0·7
0·6
a
72
27
1
b
46
39
13
c
42
54
4
d
a MAINSEAM TOP BLOCK STAITHES (111)
b MAIN SEAM TOP BLOCK LUMPSEY MINE (119)
c MAIN SEAM - SKELTON BECK TWO FOOT FROM TOP
d AVICULA SEAM STAITHES (101)
e TWO FOOT SEAM AYTON MINES (261)
f TWO FOOT SEAM STAITHES (104)
g RAISDALE SEAM HARTON GILL (264)
h RAISDALE SEAM SCUGDALE (270)
13
48
33
5
0·5
e
23
46
25
6
f
20
28
42
9
g
20
40
33
7
h
APPARENT FLATENNING RATIO c/a FROM THIN SECTION

It was pointed out previously that ooliths from the Two Foot and Raisdale Seams could be distinguished from those from the Main Seam on the basis of a mechanical analysis. The difference, in fact, may arise from the preponderance of the different oolith types: in the samples studied discoidal ooliths were almost invariably smaller than ellipsoidal.

It should be stressed that flattening is not an effect of crushing or shrinkage, nor is it influenced by the shape of the nucleus. In all probability it is a growth phenomenon. The effects of crushing, spastolithisation are quite distinct and far more sporadic, (pages 156 - 162). Except in the case of superficial ooliths the shape of the nucleus has very little effect upon the final shape attained.

The modification of the nucleus to the preferred shape takes place very early in the growth cycle of a discoidal oolith, usually by the accumulation of non-orientated chamosite at what later becomes the equator ~~(fig.)~~. Once this stage has been reached the shape is maintained by the deposition of orientated mineral. The degree of equatorial dilation in the envelope depends upon the shape of the nucleus, but may be considerable (plates 8c, b) Should too great a degree of sphericity be acquired it is common for further accumulation of non-orientated material to take place at the equator before orientated deposition is resumed. By this means equatorially dilated layers of chamosite are built one upon another towards the modal size and shape. Apparently the facility to accumulate unorientated chamosite is lessened or less necessary as an oolith nears completion, for the periferal layers are always dominated by orientated mineral. A change in an oolith's shape requirements at this late stage may also be manifested by the onset of preferential polar deposition which enhances the sphericity.

The importance of unorientated chamosite in this process stands out, and it may be that even the dilation of apparently orientated material results from the interlamination of small quantities of unorientated material. The occurrence of unorientated chamosite without equatorial dilation in some ellipsoidal ooliths indicates either that preferential accumulation was not being encouraged by the environment of deposition or that the causes of disorientation were different. Both these situations probably apply in different cases.

c) Roundness

Ellipsoidal and discoidal ooliths alike are characterised by perfect roundness, but, since this is a diagnostic feature of the majority of ooliths, it requires little comment.

d) Implications of the geometrical properties

Several interesting facts arise from a consideration of the geometrical properties of the ooliths. The first concerns the size and shape sorting, which appear beyond the capabilities of current sorting alone, as it is manifested in clastic sediments. This is a reflection of the intervention of another factor, the ability of ooliths to grow towards equilibrium with their environment. The scarcity of ooliths less than about 0.30-0.35 mm. is probably indicative of a rapid initial growth rate, rather than of some filter process whereby the 'fine' fraction is separated from the 'medium'. However, it is possible that Greenman's (1951) correction entails a certain amount of censorship at the fine end of the size analyses (Tanner 1964). At the other end of the scale the maximal sizes are probably determined by the balance between the rate of deposition and the level of abrasion. This might explain the delicate nature of the peripheral oolitic laminae in many envelopes.

A second point of significance relates to the predominance of discoidal and ellipsoidal ooliths over spherical forms. The relative roles and modes of origin of the different types of chamosite, and especially the unorientated type, are particularly important in this respect. Excluding crushing and shrinkage effects as causes of flattening, because they do not offer a satisfactory explanation of the kind of inflation involved in the envelopes of many ooliths, one must fall back upon the primary effects of deposition and erosion. If the unorientated chamosite originates physicochemically the immediate cause lies in more rapid precipitation at the equator relative to the poles and/or greater mechanical abrasion at the poles, with consequently greater erosion and better crystal packing. The difficulty is then of explaining why precipitation should be preferred at the equator and/or abrasion at the poles.

If some organic agency, algal or bacterial, is responsible for the accumulation of unorientated material, either by sediment trapping or interstitial precipitation, the main problem is to explain why this organism prefers to live at the oolith equator.

It seems unlikely that shape should be an innate property of each individual oolith, rather it appears to be imposed by the environment. In order that a preferred shape be maintained throughout the growth of a discoidal oolith it is necessary for that oolith to maintain a relatively constant orientation with respect to some surface and/or vector in the environment. The surface in this case would be the sea bed and the vector, current. Current is the important factor because it carries the components of chamosite for physicochemical deposition and the nutrients necessary for organic growth, while it also determines the relative degree of abrasion.

Both biochemical and physicochemical deposition might be expected to be greatest where the current impinged most strongly and with the most turbulence against the growing oolith; in this case presumably at the equator. The degree of preferred deposition should therefore be dependent upon the sensitivity of the depositional process, the persistance of the current, and the consistancy of the ooliths' orientation. This kind of consistance could only be expected in a gentle current regime, in which an oolith was allowed to remain relatively undisturbed upon the sea bed, especially in the early stages when shape was being initiated. An even bottom surface would obviously be a prerequisite of formation. The greater susceptibility of unorientated chamosite to equatorial dilation might be explained if it originated in quicker water than the orientated mineral, which perhaps formed during periods of greater turbulence when the ooliths were being lifted into suspension and subjected to abrasion.

From this argument it may be inferred that ellipsoidal ooliths are indicative of greater current activity than discoidal and therefore that the ooliths from the Main, *Pecten* and *Avicula* Seams, on the whole, originated in slightly more agitated conditions than those from the Two Foot, Raisdale and Osmotherley Seams (see also pages 289-290).

6. Foliaceous envelopes

The adjective foliaceous is used here for the designation of a second type of oolitic envelope, quite distinct from the normal concentric type, which is observed rather rarely in the ironstones, and has not been described previously. It refers to envelopes

PLATE 9 Foliaceous ooliths

a) Foliaceous envelope on sideritised oolith nucleus. Main Seam, Upleatham. x ~~290.~~ 100

b) Detail of above showing algal encrustation. x ~~1,200.~~ 400

c) Foliaceous envelope hanging loosely about normal oolith nucleus. Main Seam, Upleatham. Crossed polars x ~~290.~~ 100

d) Thin encrustation surrounding two ooliths. Main Seam, Skelton Beck. x ~~290.~~ 100

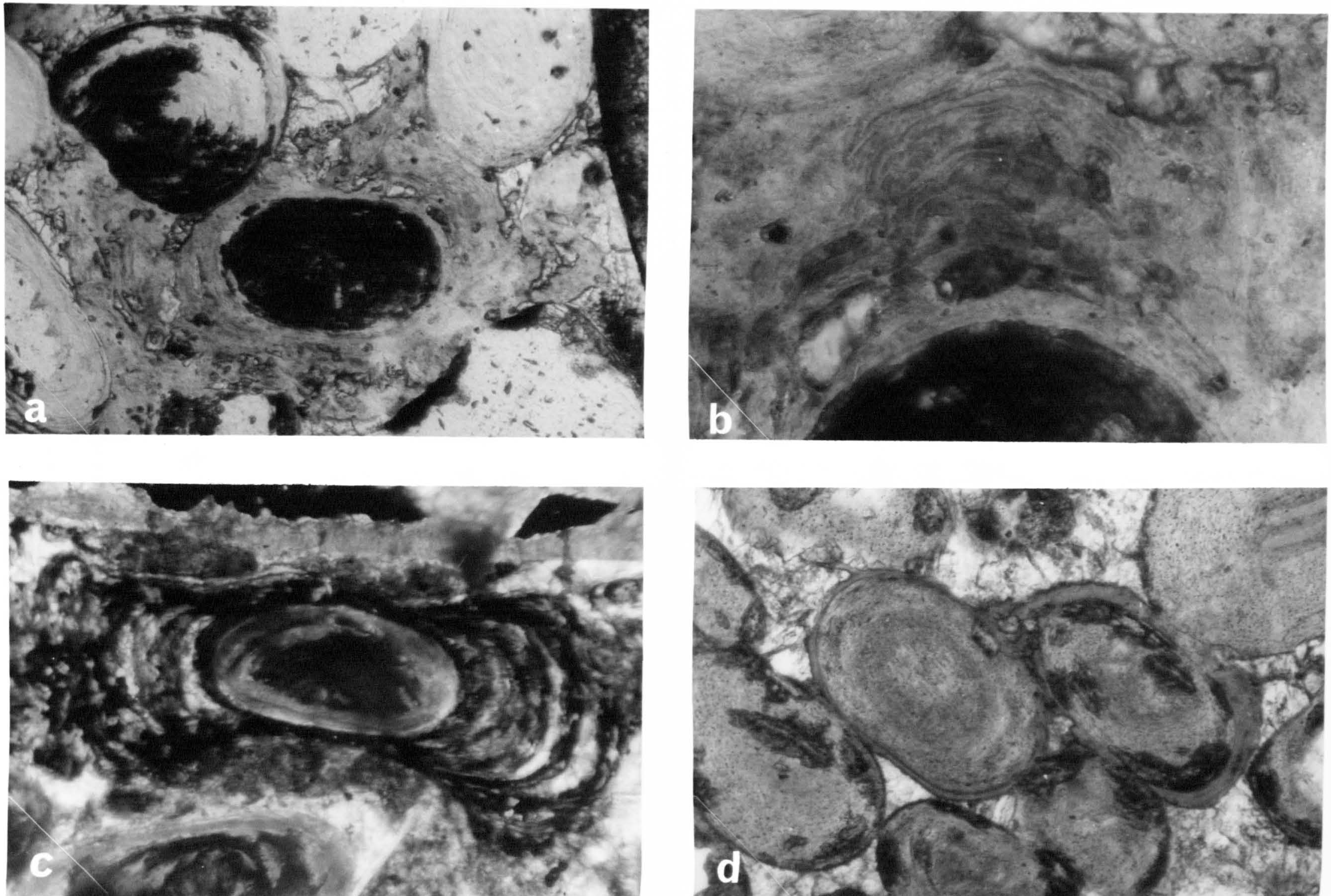


PLATE 9

which are characteristically crudely and irregularly layered, without the delicate lamination of normal envelopes, and in which the layers give the impression of hanging loosely upon the nucleus and upon each other (plates 9,10).

In rocks where this type of envelope occurs most commonly, (in the intraclastic facies of the Main Seam), the primary mineral appears to be a grass green chamosite, contrasting strongly with the olive green of the associated normal ooliths, but similar to that of the enclosing mud matrix. This resemblance is strengthened by a random orientation among the chamosite crystals, which therefore appear isotropic in polarised light, and by the occurrence within the layers of early diagenetic siderite rhombs of the type which usually occur only in the matrix (pages 207,208). In other occurrences it is more difficult to determine the primary mineral, because of subsequent replacement, but there seems no reason to suspect that it was other than chamosite.

Upon close examination of the chamosite layers, irregular scalloped or frilled laminations may sometimes be observed, which arise from the presence of small amounts of impurity, (plate 9b) but no preferred orientation among the chamosite crystals is observable.

The irregularity of the layers themselves is the consequence of deformation caused by the adjustment of these envelopes to the

PLATE 10 Foliaceous ooliths

a) Main Seam, Normanby x ~~500~~. 170

b) Black Hard, Staithes x ~~260~~. 90

c) Raisdale Seam, Hawsker x ~~260~~. 90

d) As c) above.

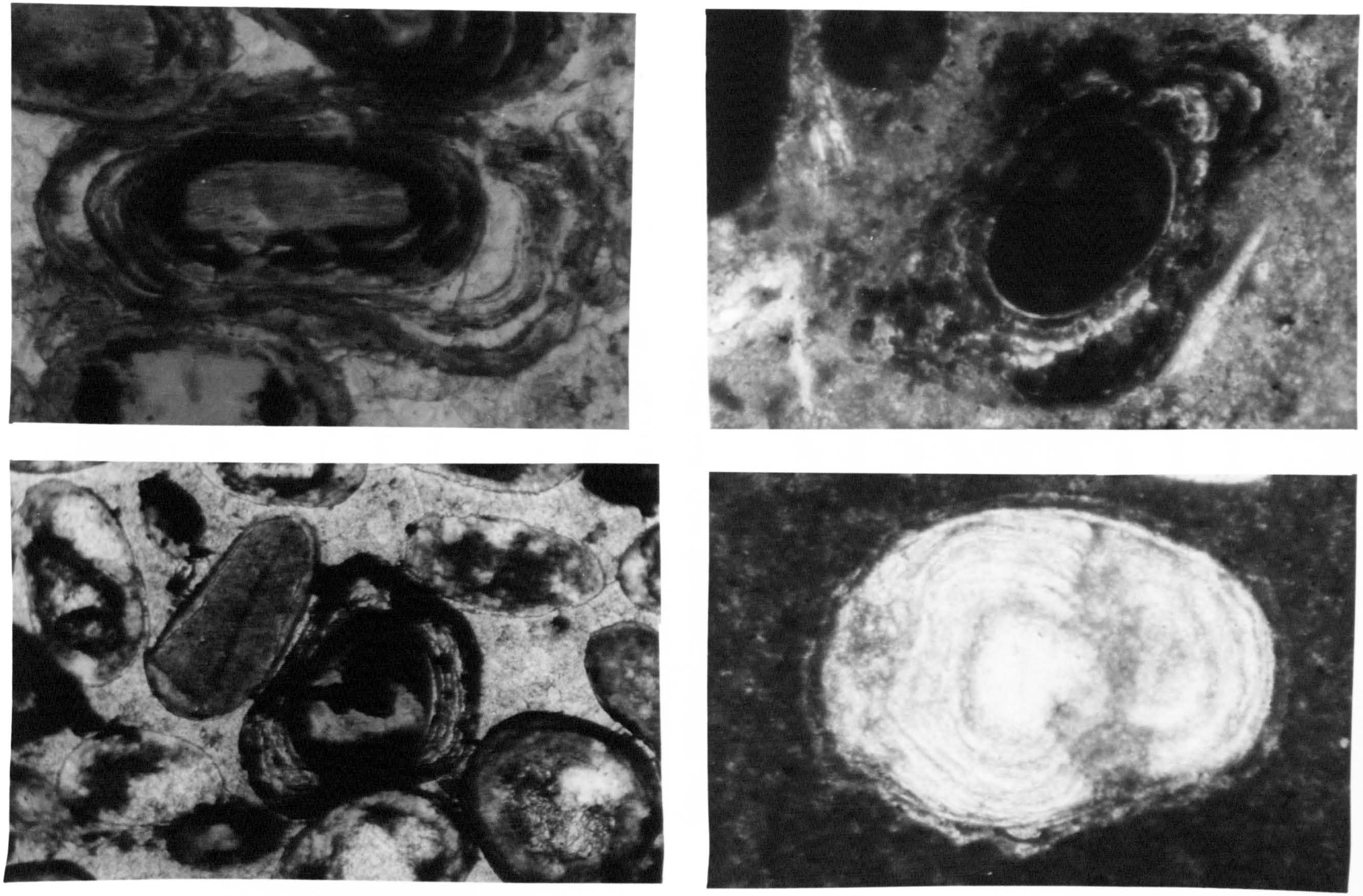


PLATE10

grain framework of the surrounding rock at a time when the chamosite was still soft. This adjustment appears to have taken place in part during compaction, but also at the time of growth. The way in which some envelopes grade imperceptibly into the structureless chamosite mud of the matrix strengthens the probability that the foliaceous envelopes are the result of sediment binding within an existing grain framework. The most likely type of sediment binder would be an encrusting alga, which would account for the scalloped nature of the laminations; (scalloped algal layers are figured by Anderson 1950, pl. II, III, IV).

The looseness of the layers, one upon another, results from shrinkage within the envelope, or from preferential solution of some layers, but in either case presumably took place subsequent to the process of sediment binding and will therefore be discussed in a later section (pages 164-165).

Since foliaceous ooliths are frequently nucleated upon normal ooliths or intraclasts of similar size, on the whole they tend to be larger than the majority of ooliths, reaching a maximum observed size of 1.6 mm. As would be expected they lack the roundness and sphericity of normal ooliths although they retain an overall concentric structure.

B. INTRACLASTS

1. Definition

The term intraclast was coined by Folk (1959) for carbonate (limestone) grains thought to have been derived by the local reworking of penecontemporaneous sediment. However, it may usefully be extended for the description of similar grains from a variety of sedimentary environments. As pointed out by Hallimond (1925) grains of this type make a very significant contribution towards the grain frameworks of sedimentary ironstones.

2. Intraclasts and Lumps

In recent limestones the intraclasts are of two kinds. The first which Wolf (1960) prefers to isolate by a separate term, lumps, are formed by the aggregation of lesser grains of clay and silt size (mud aggregates) or of sand size (grapestone aggregates). Various means of aggregation are described by Purdy (1963, 343-346), which operate either on the sea bed or in the superficial layers of the sediment. Only the gentlest reworking is, therefore, required for a supply of aggregate grains. Since the component grains, and the bonds between them, may be extremely delicate, the aggregates are fairly easily disrupted or obliterated. Thus although they may well have made an ephemeral contribution to the Cleveland Ironstones they are not readily identifiable in the lithified sediments. Neither compound ooliths nor botryoidal mudstone grains are common, although the latter may occur occasionally as the nuclei of ooliths.

Rather unusual intraclasts are the broken internal casts of gastropods, which occur in some shelly ironstones, (plate 11d). They are apparently derived through the reworking of these fossils after the dissolution of their aragonite shells (see page 135).

The most important intraclasts in these ironstones, and in ancient sediments generally, are grains of consolidated and semi-consolidated sediment derived by more vigorous erosion than that necessary to provide aggregate grains.

3. Lithology (plates 11a,b,c)

A wide variety of lithological types are represented and may usually be matched with their undisturbed equivalents. These include both clastic and non-clastic sediments. The clastics are almost exclusively shales and silty micaceous shales, sometimes with a crude lamination relict by the micas or through preferential replacement. In many, however, replacement has led to the complete loss of internal structure.

The whole spectrum of muddy ironstones, mudstones, wacke-stones and muddy packstones are represented among the non-clastic lithologies, for the most part corresponding with those known *in situ*. Types with a primary porosity, however, are exceptionally rare due to the absence of aggregate grains and because with few exceptions cementation had not been initiated at the time the intraclasts were eroded.

PLATE 11 Intraclasts

a) Sandy mudstone partly coated with oolitic laminae. Sulphur Band, North Skelton.

b) Poorly consolidated oolitic intraclast. Two Foot Seam, Staithes.

c) Phosphatised oolitic intraclast. Main Seam, Skelton Beck.

d) Gastropod cast with columella. Main Seam, Staithes. x ~~200~~. 70

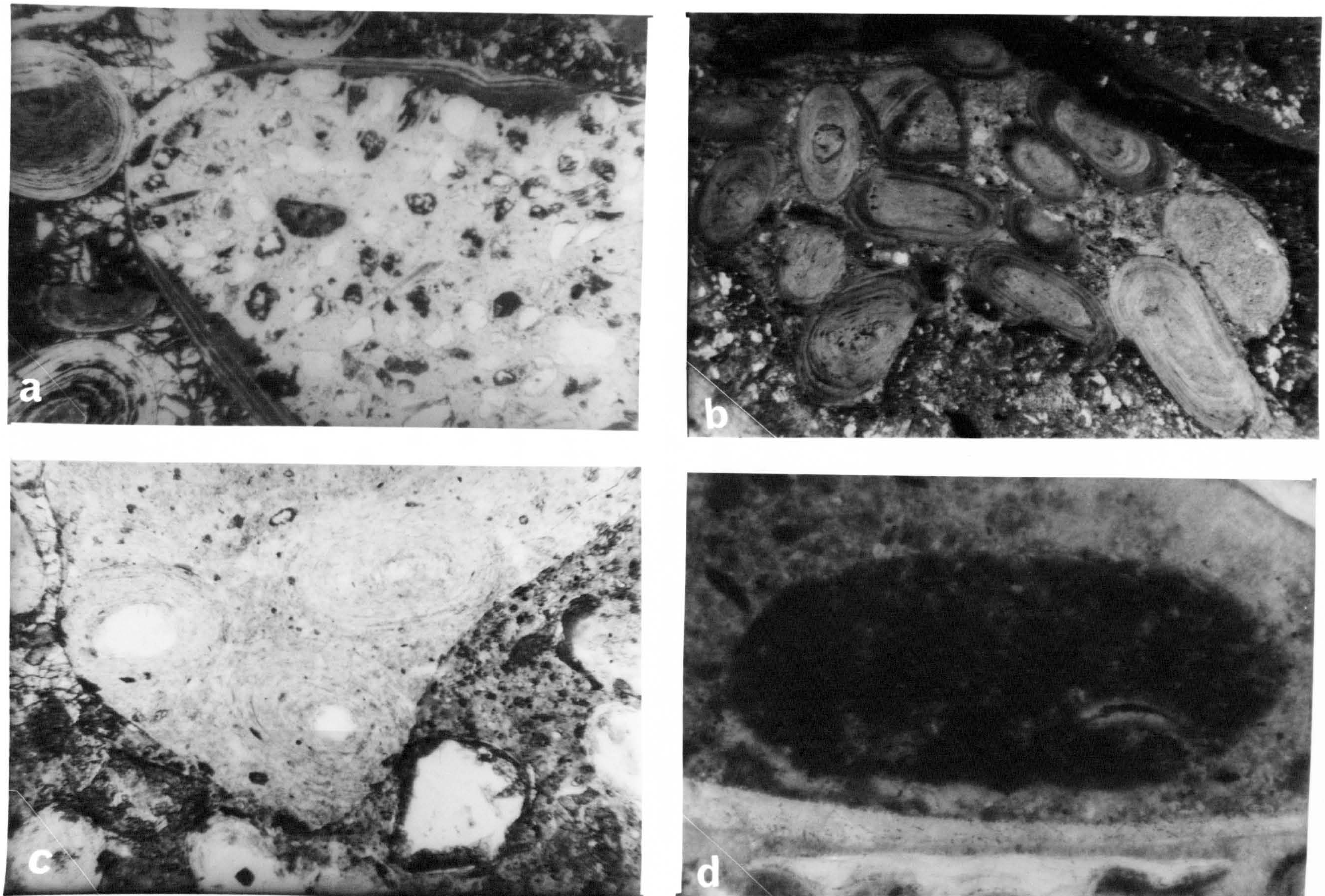


PLATE 11

4. Lithification

Clearly many of the intraclasts were only poorly consolidated at the time of incorporation for they reveal plastic deformation both by their internal and external appearance, (plate 11b). Others, however, appear to have been consolidated either prior to erosion or during transportation; many of these intraclasts have suffered early diagenetic replacements, for example siderite for chamosite, before they were eroded, or have been subject to halmyrolitic alteration during transport (plate 11c). Thus while some intraclasts show no apparent evidence of deformation, others appear to have obtained a degree of rigidity subsequent to plastic deformation.

5. Phosphatisation (See also pages 195-196)

Of primary halmyrolytic replacements (i.e. taking place before burial) phosphatisation is the most important. Although it is not exclusive to the intraclasts, there is no local source of phosphatised sediment sufficient to account for the occurrence of these intraclasts, unless it lies beyond the reach of the present outcrops. In these circumstances it seems more likely that this kind of replacement took place on the sea floor subsequent to the erosion of the intraclastic sediment.

The presence of phosphate was confirmed by staining (Mann 1950) but may also be detected in thin section due to the brown colouration of the mineralloid collophanite. The amount of phosphate present is indicated by the colour and transparency; pure collophanite appears golden brown and transparent in thin section while the impure mineral~~l~~oid is grey brown and earthy.

Phosphatisation probably plays an important role in the lithification of intraclasts on the sea floor. Thus while phosphate may be absent from poorly consolidated clasts, it is almost ubiquitous in their consolidated counterparts, usually to the detriment of their internal structure.

6. Size, shape and roundness

The size, shape and roundness of the intraclasts varies considerably. They occur in all size grades up to a maximum of about 5 cm., although below 0.5 mm. they are generally restricted to the nuclei of ooliths. They are always poorly sorted and give rise to positively skewed distributions when mixed with ooliths; for example see figure 31a. Characteristically they are poorly rounded, and have low sphericities, especially if they have been subject to plastic deformation.

C. FAECAL PELLETS

1. Definitions

"Small rounded, spherical to ellipsoidal or ovoid aggregates of microcrystalline calcite ooze, devoid of internal structure" (Folk 1962, 64) have been shown to make an important contributions towards limestone sediments both ancient (Twombley 1964, p. 74-78) and modern (Purdy 1957; 1963, p. 347). Characteristically they occur in the coarse silt and fine sand grades, and often show a remarkable uniformity of size through one deposit. The greater part of these grains are interpreted as faecal in origin, although some may arise in other ways, for example by purely mechanical aggregation, (Purdy 1963). They are distinctly different from intraclasts, therefore, and can usually be readily differentiated from them, although difficulty may arise in the finer sand grades.

2. Occurrence

Similar pellets, with the same properties of size and sorting have been observed from a number of horizons in the Cleveland Ironstone Formation and are similarly attributed to a faecal origin. In the Main Seam, the smallest pellets range in size between about 005 mm. and 0.10 mm. with an elongation of up to 2:1, allowing for the effects of sectioning (plate 12a). Others are slightly larger (diameter 0.15 mm. and lengths up to 0.6 mm.) and are distinctly rod shaped, (plate 12b). They are composed of mud almost identical to that of the matrix, from which they are distinguishable only in the presence of siderite spar, or through slightly greater turbidity. The size sorting, shape and texture of these grains strongly suggest a faecal origin although it is not possible to say from what animals they were emitted.

Plates 12a,b,c indicate the acute difficulty of identifying faecal pellets in mudstone facies especially after sideritisation

PLATE 12 Faecal pellets and chamosite flakes

a) Interstitial pellet material. Main Seam, Staithes.

b) Pellets from inside ammonite chamber. Middle Band, North Skelton.

c) Cloudy pellets replaced by calcite. Main Seam, Staithes.

d) Chamosite flakes, shell, pellet and plant debris. Two Foot Seam, Rosedale.

X ~~200~~ 70

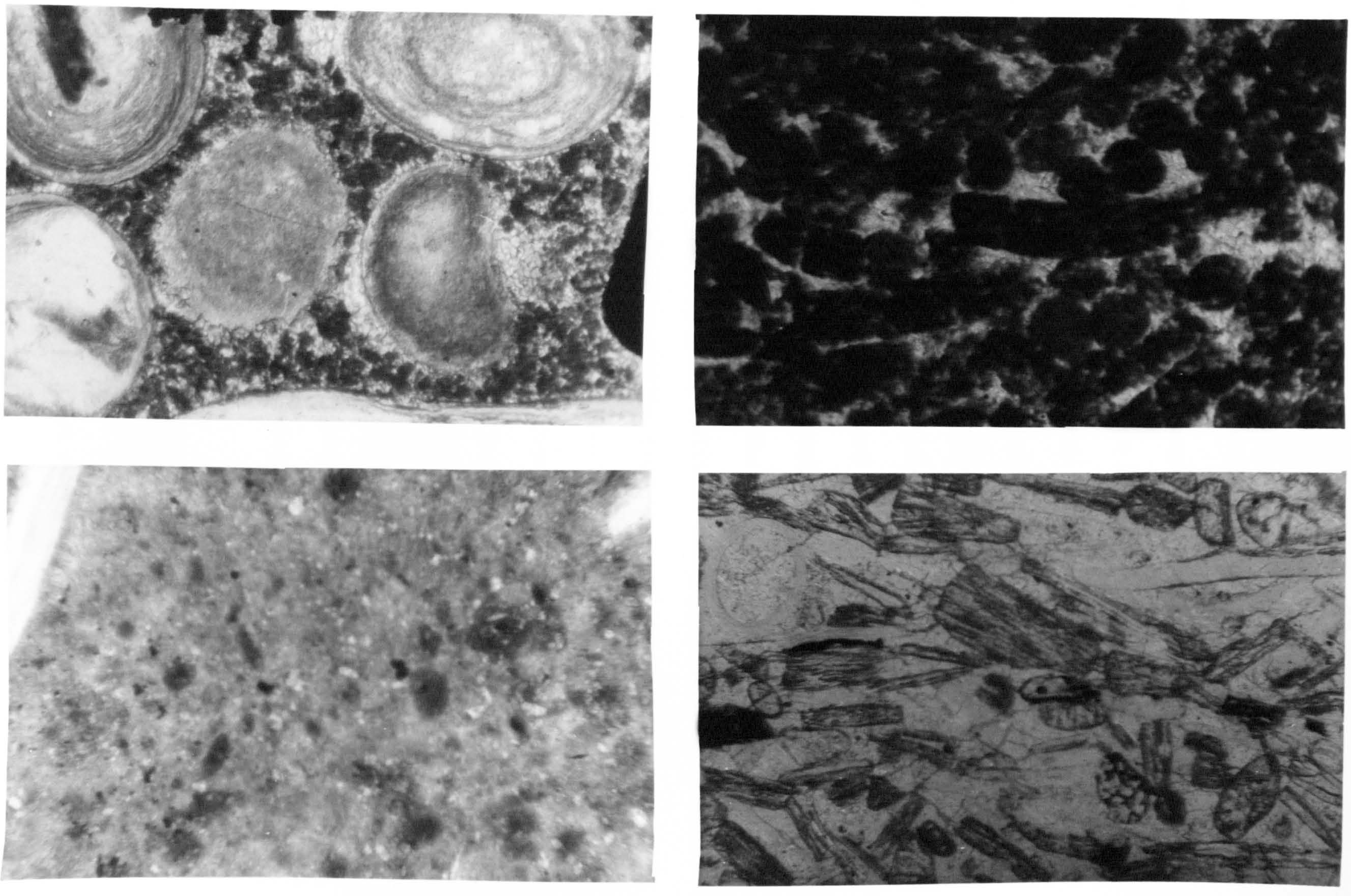


PLATE 12

or siderite grain growth. Many siderite mudstones have a blotchy appearance possibly caused by the presence of pellet material; in others every trace of primary texture has been obliterated. One of the most favourable conditions for pellet preservation occurs in shelly mudstones in which the matrix has undergone replacement by calcite. Here it is the greater turbidity of the pellets which distinguishes them from the matrix (plate 12c).

It is very difficult to estimate the total contribution made to the grain frameworks by these pellets. This is especially so since siderite predominates in the finer grained mudstone facies where the pellets occur. Large quantities of faecal material must have been evacuated by the prolific fauna associated with the ironstones, but what fraction survived the processes of disruption on the sea floor in pellet form is impossible to say.

Porrenga (1966; 1967) has shown that under certain circumstances faecal pellets provide a very favourable site for iron mineralisation and it may be that the presence of faecal matter in one form or another, through its effect on Eh and pH, plays a decisive role in the distribution of silicate and carbonate facies in the ironstones (pages 321- 327).

D. CHAMOSITE FLAKES

1. Definition

Chamosite crystals ranging from clay (in the matrix) to medium sand size occur abundantly in ironstones in which chamosite is an orthochem. However, the present section is only concerned with the larger of these crystals, those greater than 0.03 mm.

2. Occurrence

The majority of such single crystals occur as the nuclei of ooliths (pages 107-108), but a small percentage (usually less than 1% of the grain total) occur without oolitic coatings. The most conspicuous flakes occur in the fine to medium sand grades. Unprotected by an oolitic envelope the flakes are frequently found crushed, broken or replaced so that they are far less suitable for optical examination than those described previously.

Chamosite flakes occur in all seams but are especially common in the Two Foot and Raisdale Seams. Of these more than 90% occur as the nuclei of ooliths. However, the Two Foot Seam in Rosedale yielded one thin lamina in which approximately 75% of the grains were uncoated chamosite flakes, pseudomorphed by siderite (plate

Although these grains are clearly of local derivation, in the absence of evidence of in situ growth it is impossible to say whether they formed synsedimentarily on the sea floor or by authigenesis in the chamosite muds. The latter seems more likely (see pages 194).

E. SKELETAL GRAINS

1. Definition

Skeletal grains are those derived from the endo- or exoskeletons of organisms. This designation is recommended by Wolf (1960) rather than the terms shell and fossil, which each have a slightly different connotation; shells are only one type of skeletal grain, while fossils are not necessarily skeletal.

2. Occurrence

The ironstone seams are richly fossiliferous, and not surprisingly skeletal fragments occur in most thin sections, although usually as a relatively minor constituent of the whole rock. In the majority of grain supported fabrics, they form only a very small percentage of the framework (less than 5%). However, shelly lenses, which occur in most seams, are exceptional; and in here the total framework may be provided by skeletal debris. In mud supported rocks the percentage remains low, but the apparent importance of these grains is increased by a relatively rapid fall off in the percentages of ooliths.

Most fossiliferous of all the seams, although otherwise quite distinct from each other, are the *Pecten* and Two Foot, which contain shelly beds or lenses throughout much of their thickness. The Main, Raisdale and *Avicula* Seams are especially fossiliferous at many localities, but less consistently so over the area as a whole. This leaves the Osmotherley Seam, the least fossiliferous of the six.

3. Identification in thin section

The whole problem of identifying organisms in thin section was reviewed systematically by Cayeux (1916, p. 310). Three main lines of evidence may be brought to bear, their relative value

PLATE 13 Shell microstructures

a) Tetrarhynchia tetrahedra: prismatic calcite with punctae.

b) Astarte: lamella aragonite pseudomorphed by calcite.

c) Liostrea: calcite cross lamella structure dark bands growth lines.

d) Pseudopecten equivalvis: calcite chevron cross lamella structure

x ~~325~~.
110

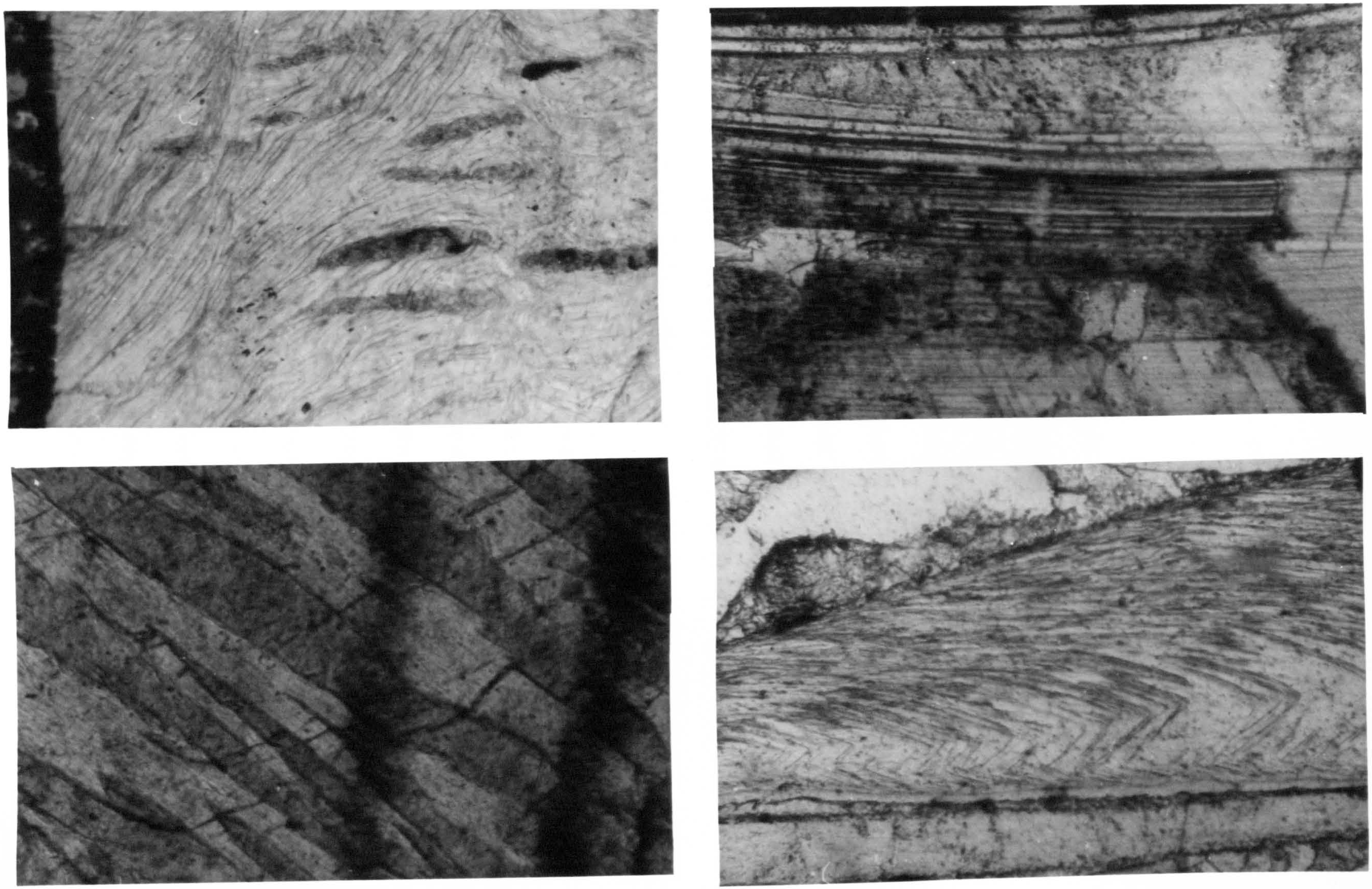


PLATE 13

depending upon the size and mode of preservation of the fragment in question.

a) Morphology and ornamentation

The value of morphology depends upon the size of the grain in thin section relative to the complete endo- or exoskeleton. In the present case the skeletal fragments are usually sufficiently large for a distinction to be made between different phyla and between the various classes of mollusca. However, some difficulty arises in separating brachiopods from certain lamellibranchs.

Some types of surface ornamentation such as ribbing (*Pseudopecten*, *Limea*, *Oxytoma*, *Protocardium*, etc.) are diagnostic even on quite small fragments.

b) Mineral composition

The distribution of calcite and aragonite in different phyla is discussed by Hatch, Rastall and Black (1938, pp. 155-160). Both aragonite types (ammonites, gastropods, scaphopods, lamellibranchs, foraminifera) and calcite types (brachiopods, echinoderms, belemnites, lamellibranchs, ostracods, foraminifera) occur in the Cleveland Ironstones, although no trace of aragonite remains in the skeletal grains. Because of the instability of aragonite it has been consistently replaced by pseudomorphic minerals during diagenesis. Only very occasionally is there evidence of replacement in calcite shells and then only under conditions of extreme sidéritisation.

The pseudomorphs include ferroan calcite, siderite, kaolinite and sphalerite (page 256). It was found that the recognition of pseudomorphed aragonite grains from original calcite grains was greatly facilitated by staining with a mixture of alizarin reds and potassium ferricyanite ~~(see appendix)~~. In specimens stained in this way original calcite (non-ferroan) appears pink, pseudomorphic calcite (ferroan) violet or blue, while other minerals remain unstained. The technique was particularly useful for the separation of anisomyarian lamellibranchs (mainly calcite) from eulamellibranchs (aragonite). A list of probable calcite and aragonite genera from the ironstones is given in table 8.

c) Internal micro-structure

Micro-structures are only completely preserved in original calcite skeletal grains, although relict structures are occasionally visible in pseudomorphs (plate 13b). Like ornamentation these structures can be diagnostic even in quite small fragments, as long as the effects of random sectioning are taken into account. Micro-structure provides the most useful criterion for distinguishing between brachiopods (plate 13a) and lamellibranchs (plates 13c,d,14a) and for identifying different species. Plates 13c,d and 14a for example show three different manifestations of lamellibranch cross-lamella structure (Lucas 1952, pp. 246-261) which are useful in the identification of *Ostrea*, *Pseudopecten* and *Entolium*.

4. Skeletal disarticulation, breakage and abrasion

The faunal assemblages of the ironstones appear to be mixed life and indigenous death assemblages (Hallam 1960). This implies that a part of the fauna, in fact the greater part, (shallow infauna, epifauna and nekton), has undergone local transportation and has consequently been subject to disarticulation, breakage and abrasion. The degree of destruction depends on a number of factors including the strength of each skeletal particle relative to its size, the rate of deposition and burial, and the energy of the environment of deposition (Folk and Robles 1964).

Because of differences in morphology, mineral composition and internal microstructure some skeletons are more rapidly disintegrated than others. Excepting infaunal lamellibranchs not subjected to erosion, the only articulated forms (lamellibranchs, brachiopods, crinoids and ostracods), which consistently escape disarticulation are the brachiopods.

Breakage appears least among the microfossils, although belemnite guards, and crinoid ossicles seem fairly robust. The dominant faunal group, the lamellibranchs, is also the most prone to breakage. Some thick-shelled forms (the valves of Pseudopecten and Ostrea) survive even in high energy deposits, but thin shelled aragonite valves rarely escape breakage.

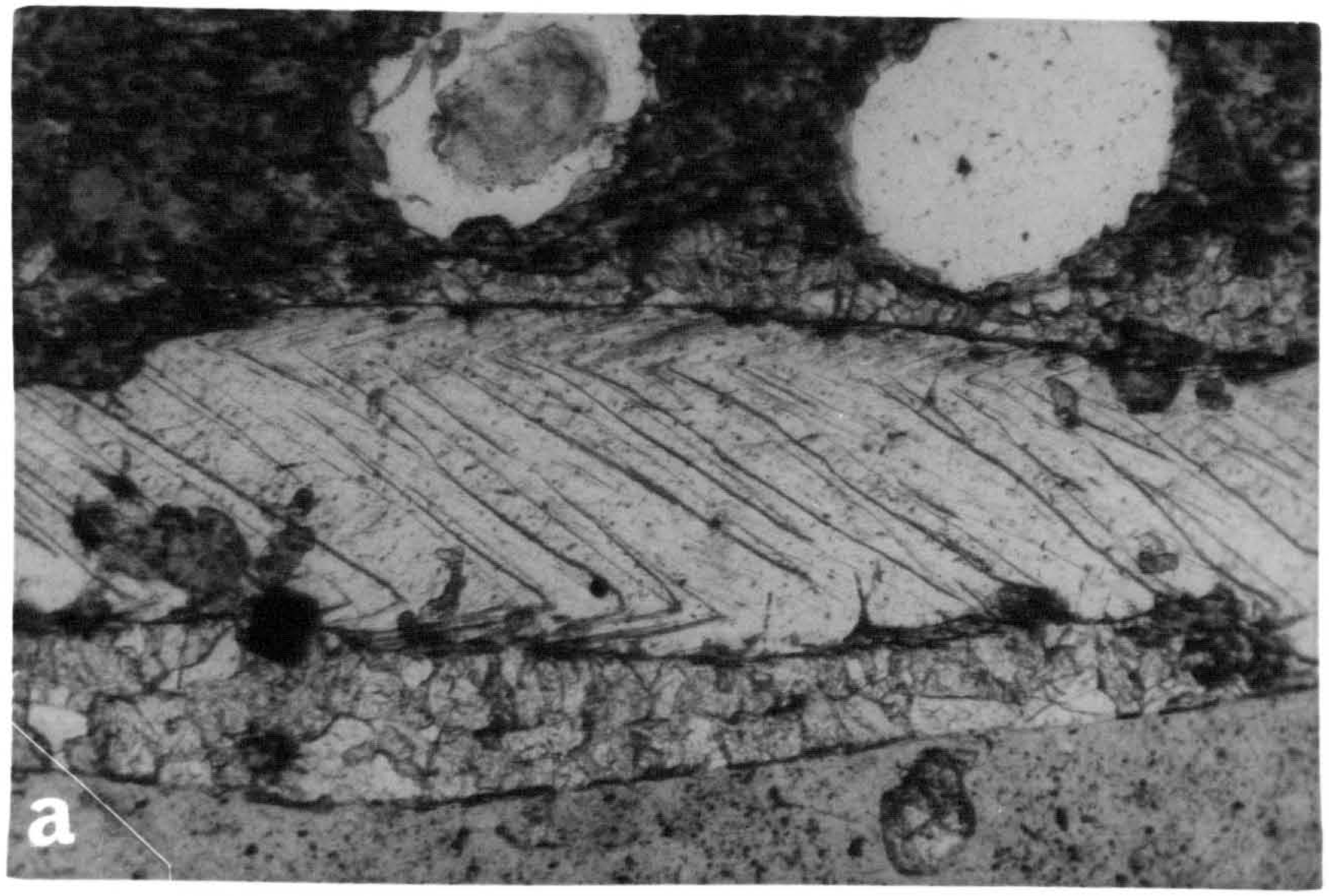
The relative degree of breakage and abrasion in the various skeletal grains is obviously a useful guide to the energy level in

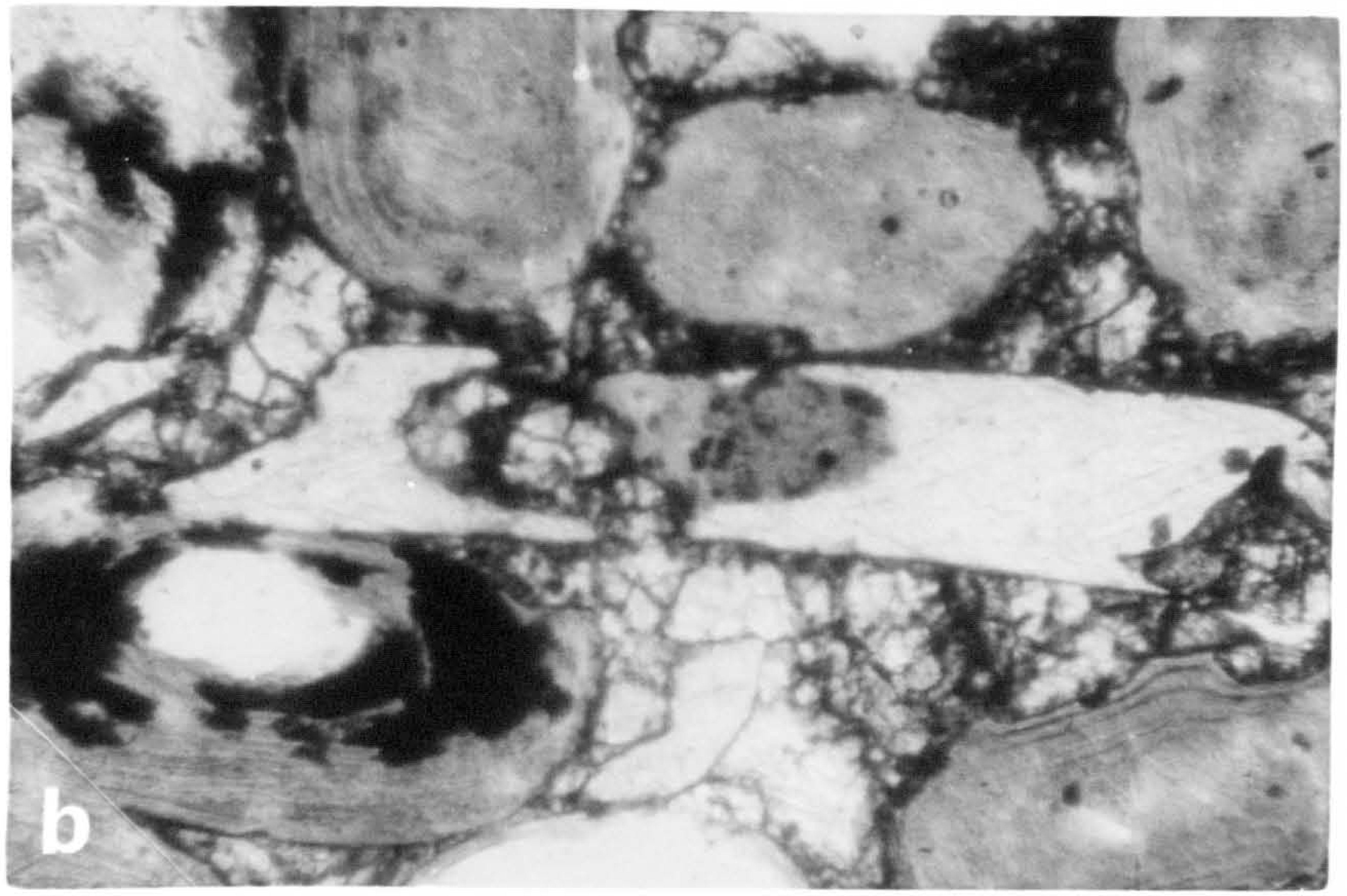
PLATE 14 Shells

a) Entolium: calcite chevron cross lamella structure x ~~200~~. 70

b) Zapfella? boring in shell x ~~300~~. 100

c) Zapfella? boring and two types of ' algues perforantes' x ~~300~~. 100





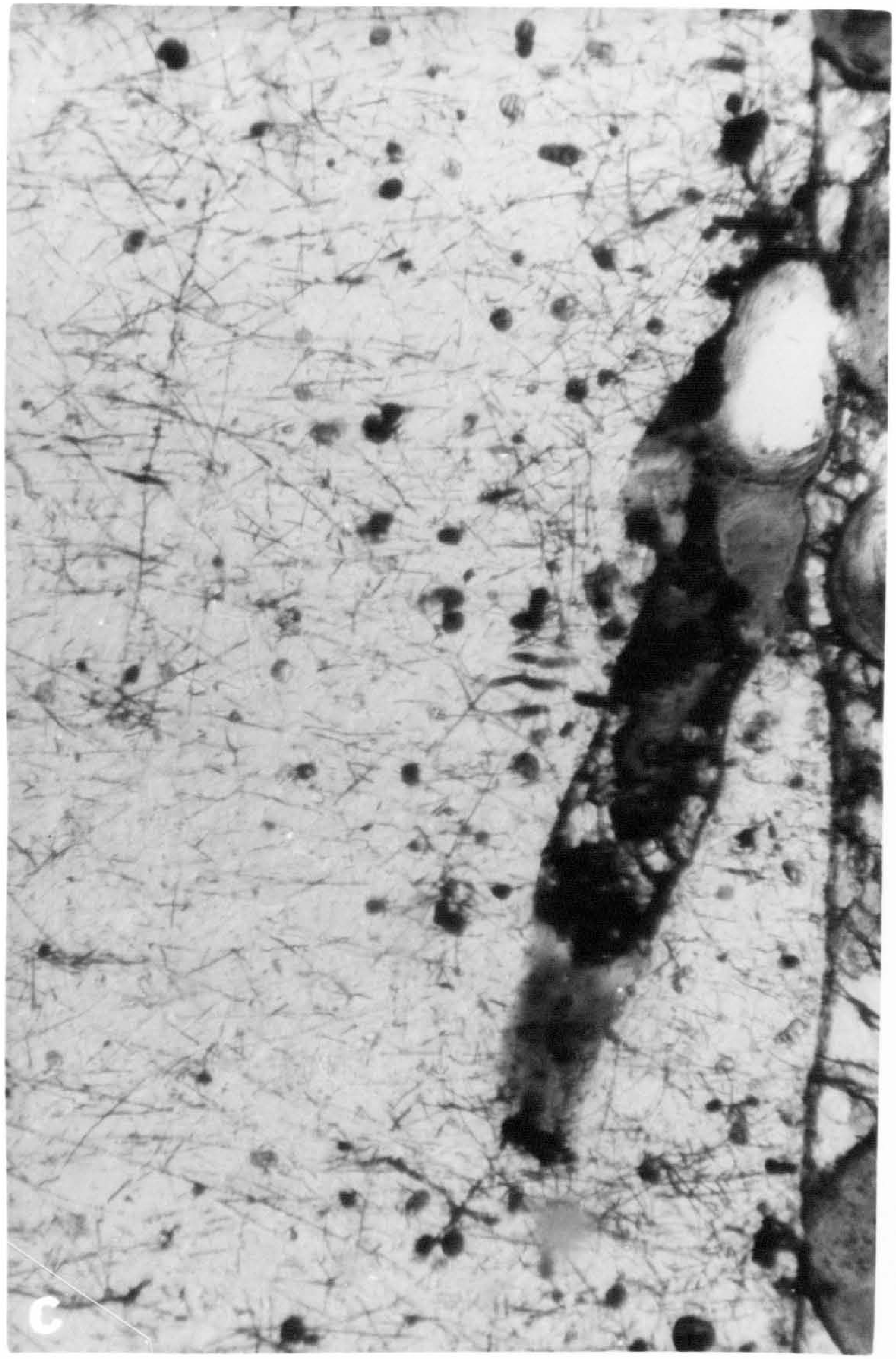


PLATE 14

the environment of deposition, (i.e. to the amount of agitation). The most abraded skeletal fragments occur in grainstone and sparry packstone facies (Main Seam and Two Foot Seam), while lenses of unbroken lamellibranch valves are only characteristic of the mudstone facies (e.g. Pecten Seam, Main Seam and Avicula Seam). However, it must be remembered that breakage and abrasion are also a function of the length of time a skeletal grain is available on the sea floor, which depends on the rate of deposition.

5. 'Algues perforantes'

Shell boring by algae and other organisms provides another means by which skeletal grains are broken down. Plate 18c illustrates a belemnite guard riddled by anastamosing tubes of the type attributed to filamentous algae ('algues perforantes') by Cayeux (1914, 1916). The tubes, now filled with calcite or siderite cement, reach a maximum diameter of about 5μ, averaging 2μ, and may be several hundred times as long as they are wide. They are apparently branching but most notable for their straightness. The same guard bears two other types of perforation. The first consists of tubular borings of average diameter about 30μ infilled with mud or spar. The second type is much larger and consists of sack-like excavations of the type described from Gryphaea shells from the Frodingham Ironstone (Hallam 1963) and attributed to the cirripede Zapfella (Saint-Seine 1954).

Clearly in the case of belemnites all the borings must have been made after death, but with lamellibranchs it is possible that some were made during life.

Table 8

Aragonite Lamellibranchs

Taxodonta	Leda
Anisomyaria	Modiolus
Eulamellibranchia	Protocardia
	Cardita
	Ceromya
	Gresslya
	Pleuromya
	Ptoladomya
	Goniomya
	Hippopodium
	Unicardium
	Astarte

Calcite Lamellibranchs

Pseudopecten	mainly calcite
Entolium	mainly calcite
Limea	mainly calcite
Oxytoma	mainly calcite
Plicatula	entirely calcite
Ostrea	entirely calcite

F. RELATIVE ABUNDANCE OF ALLOCHEMS

The relative abundance of the major allochems (intraclasts, ooliths and skeletal debris) in grain rich and grain poor facies is illustrated in figures 34 and 35 by reference to the Main and Two Foot Seams, which were chosen for modal analysis, because of the wide spectrum of rock types available. As a resultof the scarcity of grain rich types in the other seams, none offered the same scope. The grain fields have been divided in the manner suggested by Folk (1959, 1962) with an additional subdivision in the oolite field as recommended by Imbrie and Purdy (1962).

1. Grain rich facies (grainstones and packstones)

The overall predominance of ooliths which stands out in both diagrams, may have particular significance in grain rich ironstones.

From his investigations of grain rich rocks from the Bahamas, Purdy (1961, 1963b) found that a subdivision at 85 percent ooliths was useful in separating high oolite shoals (sites of optimum conditions for oolith formation) from mixed oolite shoals, derived by reworking. The same division has been found applicable in the present work, although a direct comparison with the Bahaman analyses is not possible. In the first place the relative rates of allochem production were probably different; the production of skeletal debris, in particular is likely to have been lower in the ironstones. Although local biostromes occur there is no suggestion that the oolites were ever associated with extensive biohermal or biostromal deposits. Secondly the high oolite

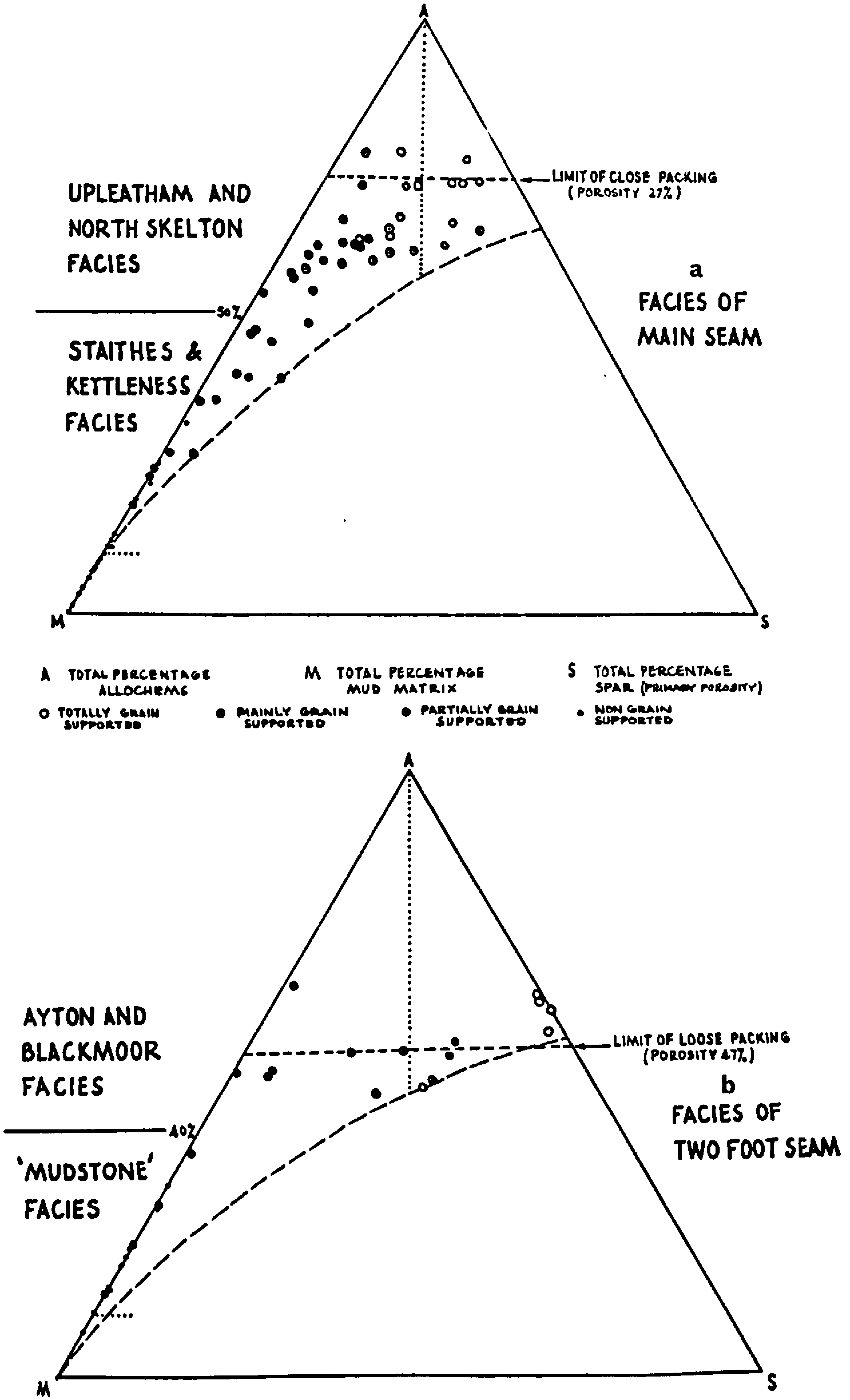


FIG. 34. COMPARISON OF FACIES FROM MAIN AND TWO FOOT SEAMS.

deposits among the Cleveland Ironstones contain up to 50% more mud than Bahaman high oolite shoals (Virtually mud free).

Nevertheless in the absence of any internal evidence of major sediment redistribution, either by currents, slumping or turbidity flow, the high concentration of this relatively rare grain type in the high oolite facies undoubtedly indicates the proximity of autochthonous oolite shoals. The majority of the matrix appears to have been fixed in the deposits as a result of the activity of burrowing organisms and therefore contains a high percentage of faecal debris. It may however indicate intervals of quiet water during which muds were accumulated in preference to oolites and then interburrowed with the latter by the infauna.

Mixed oolite deposits on the other hand, because they are not infrequently current bedded and contaminated with allochem types other than ooliths, show the results of more substantial current reworking. They are in every respect analogous to the Bahaman mixed oolites.

An important difference between grain rich rocks from the Main and Two Foot Seams brought out by figure 35a is the predominance of intraclasts over shells in the former and shells over intraclasts in the latter. The precise reason for this variation is unknown but reflects the greater complexity of the Main Seam, and probably indicates a higher energy environment. Whatever the explanation the occurrence of intraclasts at a level of greater than about 5 percent, provides one means of distinguishing the Main Seam from the Two Foot Seam.

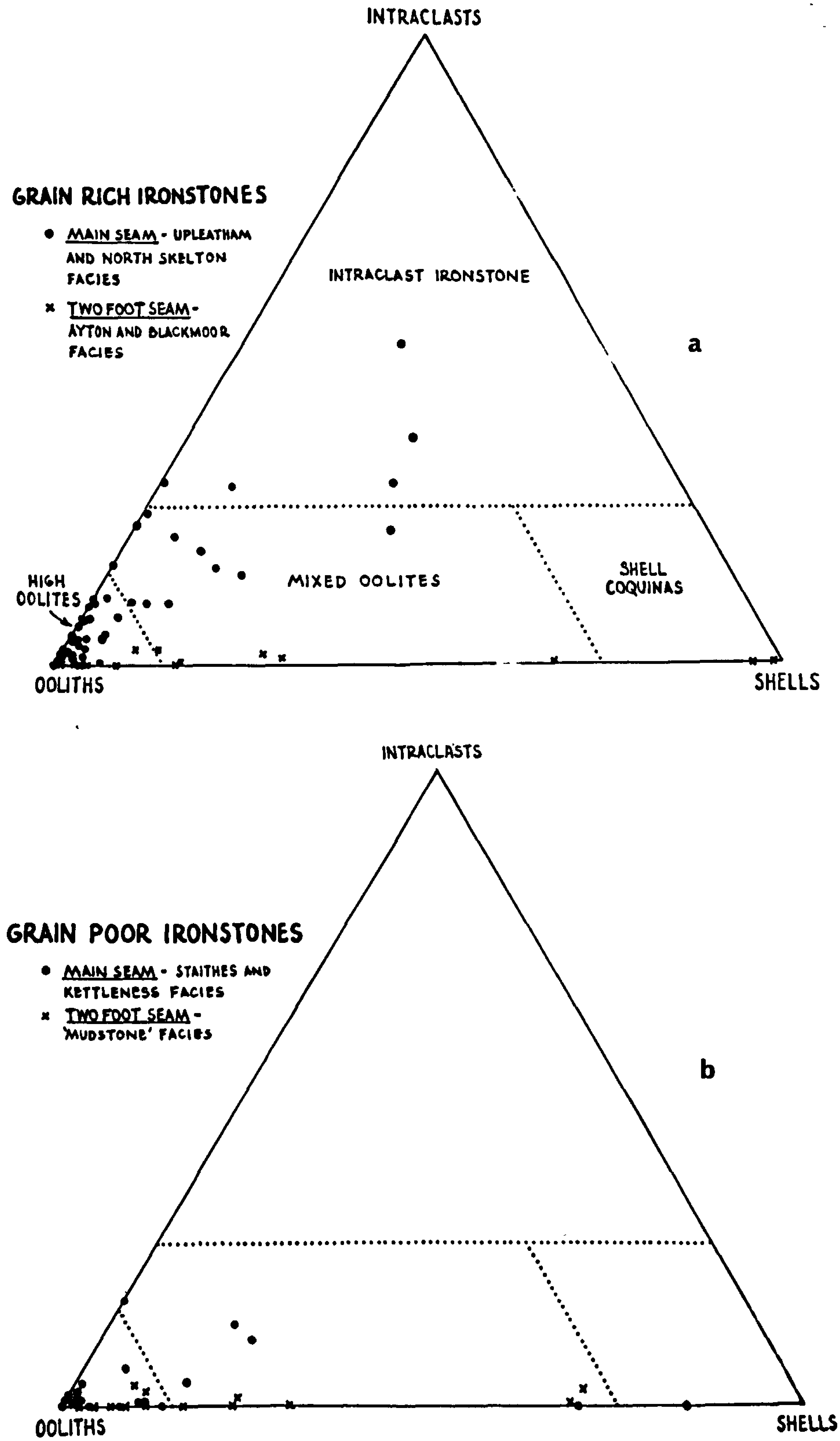


FIG. 35. COMPARISON OF GRAIN RICH AND GRAIN POOR FACIES FROM MAIN AND TWO FOOT SEAMS.

2. Grain poor facies (wackestones and mudstones)

In the grain poor facies (fig. 35b) the percentage of intraclasts falls off in all seams, and the Main Seam therefore closely resembles the Two Foot and other minor seams. Although skeletal grains gain in importance ooliths remain the dominant allochem in all seams. The subdivision of the oolite field has been retained in this diagram for comparison with figure 35a, but clearly loses its significance in grain poor facies.

IV PRIMARY MATRIX AND POROSITY

A. MATRIX

The matrix in ironstones, as in limestones, is believed to be mainly orthochemical in origin (i.e. precipitated within the basin of deposition) and therefore has an important bearing on the interpretation of the environment of deposition. However terriginous quartz, micas and clay minerals are often present as contaminants, and lead to the deterioration of an ore which marks the beginnings of a passage into terriginous facies.

1. Primary orthochemical facies

A major problem is often to distinguish between primary and diagenetic orthochems in the matrix. Chamosite and siderite, the most important minerals have each been ascribed both a primary and a diagenetic origin in other deposits. First of all then, which iron facies, oxide, silicate, carbonate or sulphide were primarily represented in the matrix of the Cleveland ironstones?

a) Oxide facies (limonite)

Where limonite is present in the matrix it is clearly a weathering product of chamosite or siderite. No primary limonite occurs. However, the possibility that iron oxides or hydrates existed prior to diagenesis, when they may have been converted to chamosite or siderite, cannot be entirely dismissed. If so their existence must have been purely transitory since both chamosite and siderite appear early in the orthochemical history.

b) <u>Silicate facies</u> (chamosite)

Chamosite mud occurs occasionally in the matrix of the *Avicula* Seam but only becomes important in the *Pecten* and Main Seams. It appears to be almost entirely absent from the Two Foot and Raisdale Seams. Under the most favourable circumstances its presence may be detected by its green colour both in hand specimen and thin section. The green colour is most strikingly displayed in the chamositic facies of the 'Black Hard' at the base of the Main Seam; the closest thing to a monophase chamosite mudstone in these deposits (Hallimond 1925, p. 47). However, partly due to the leaching of iron from the mineral, and partly through the admixture of siderite the green colour is often lost in shades of grey.

Under polarised light this mud is pseudoisotropic but is shown under the electron microscope to consist of a felted mass of crystals averaging 2μ in size (plate 16a); the same order of size as aragonite needles in modern calcareous muds, (Lowenstam and Epstein 1957; Cloud et al. 1962). Where, in a few instances, microcrystalline chamosite occurs in the matrices, it has resulted through recrystallisation and grain growth (page 194).

There is no direct evidence that chamosite was an original consistuent of the matrices, but indirectly, because it is replaced by early diagenetic siderite (pages 205), it is shown to be of very early origin. This, combined with the primary occurrence of chamosite in the ooliths, strongly suggests that the chamosite mud was also primary.

c) Carbonate facies (siderite)

Even in the chamositic facies of the Main and Pecten Seams (pages 263 - 273 & 284), siderite is not entirely absent from the matrix. As the percentage increases the green colour gives way to blue grey and grey. Thus at the base of the Main Seam 'Greenstone' passes laterally into 'Blue Mottle' and 'Black Hard'. Except in these chamositic facies siderite is the dominant constituent of the matrices in all the seams even where the ooliths are of chamosite.

Unlike chamosite, siderite is conspicuously crystalline, even euhedral in some cases. The individual crystals range in size from a few microns up to about 50μ. Especially in the coarser grain sizes it is evident that the siderite has grown during diagensis, sometimes at the expense of chamosite (e.g. in the chamosite-siderite packstones and wackestones of the Main Seam).

However after extensive sideritisation it is often very difficult to say what the original nature of the mud was. In some cases it was undoubtedly chamositic, in others it could have been limonitic or the present siderite textures could have developed by the recrystallisation of earlier siderite muds. The available thermochemical evidence, however, does not favour the supposition of a primary siderite mud (page 317).

The position of the carbonate facies between the chamosite facies on the one hand and the terriginous facies on the other suggests that siderite may develop not only at the expense of chamosite but also that of terriginous material. There is clear evidence for the replacement of chamosite in the packstone-wackestone facies and clear evidence for the replacement of terriginous material in the siderite mudstone concretions of the terriginous facies. A combination of both processes is therefore the most likely origin for the siderite of the carbonate facies. In both cases these replacements are early diagenetic (pages 260) and therefore siderite cannot be regarded as a primary constituent in the matrix of the ironstones.

d) Sulphide facies (pyrite)

Pyrite only occurs in abundance in the matrix of the 'Sulphur Band' at the top of the Main Seam, where it occurs mainly as a replacement of mudstone. Elsewhere it may be present in small percentages as pyritospheres or finely disseminated through the matrix, but always appears to be secondary in origin (page 197).

2. Terriginous admixture

The majority of terriginous material in these ironstones falls within the clay and silt grades, and although coarser grains, up to fine sand grade, also occur, the whole is counted as matrix for convenience. Terriginous grains in excess of 0.25 mm. (medium sand and upwards) are extremely rare.

The contaminants consist mainly of quartz, micas and clay minerals, which occur most commonly in the fine grained mudstone facies, and only rarely in strongly oolitic facies. This is partly due to the diminution of fine grained material in the oolites, partly due to extensive siderite replacement, but more importantly because the mudstone facies are transitional to terriginous facies. The total percentage of terriginous debris may vary considerably therefore. Further variations are also introduced by sediment mixing by the infauna. The characteristic mottling of the 'Blue Mottle' and of the Avicula and Osmotherley Seams is mainly the result of the interburrowing of siderite mudstone with shale.

Among the sand and silt grade contaminants angular quartz grains predominate. In the siderite mudstone facies of the Main Seam at Kettleness quartz silt-sand values of up to 6.5 percent were observed, but high values undoubtedly occur before the seam breaks down into shales with siderite mudstone nodules. Apparently there is a critical level at which the balance between orthochemical siderite and terriginous debris breaks down during diagenesis and the siderite is encouraged to migrate into concretions.

Micas, almost exclusively muscovite, occur up to an extent of 1-2 percent in many mudstones, but the greater part of the terriginous material, consisting of clay grade quartz and clay minerals is not readily apparent under the microscope, although it may be collected as an insoluble residue after hydrochloric acid treatment.

The most surprising thing about the terriginous admixture is its low percentage in the workable ironstones. According to Hallimond (1925, p. 51) there is no residual SiO_2 or Al_2O_5 left after chamosite and siderite are calculated for in the Upleatham facies of the Main Seam and only 10 percent in average Cleveland Ironstone, which is partly accounted for by diagenetic opal, quartz and kaolinite.

Considering the manner in which the ironstones pass laterally into terriginousshales it is most important to know how this terriginous material was excluded from the areas of ironstone development. There are several possibilities:-

(i) A 'clastic trap',

(ii) Hydrodynamic separation between ironstone minerals and terriginous material,

(iii) Chemical leaching of terriginous material and partial recombination to form iron minerals.

Neither of the first two solutions seen applicable in the case of the Cleveland Ironstones; there is no physical barrier between the ironstone and terriginous facies and the hydrodynamic gradient across the area was insufficient to separate grains from matrix in the ironstones. The author therefore favours the third possibility but this whole question is discussed in greater detail in pages 315-317 .

3. Fabric

a) Internal fabrics, the expression of inhomogeneities within the matrix, occur in muddy sediments (packstones, wackestones and mudstones) from all seams. Such inhomogeneities are usually the consequence of infaunal burrowing or of the presence offaecal material (page 130).

Burrows may range in diameter from a few millimetres (*Chondrites*) up to several centimetres (*Gresslya*, *Pholadomya*) and are usually totally infilled with mud (plate 15). Only in a few instances are burrows left

PLATE 15 Burrows

a) Longitudinal section filled with quartz silt now replaced by siderite.

b) As above, transverse section.

a) & b) Middle Band, North Skelton.

c) 'Spreiten'structure in siderite mudstone. Two Foot Seam, Bransdale.

d) Open burrow filled with siderite and later, calcite, Main Seam, North Skelton.

x ~~100~~. 30

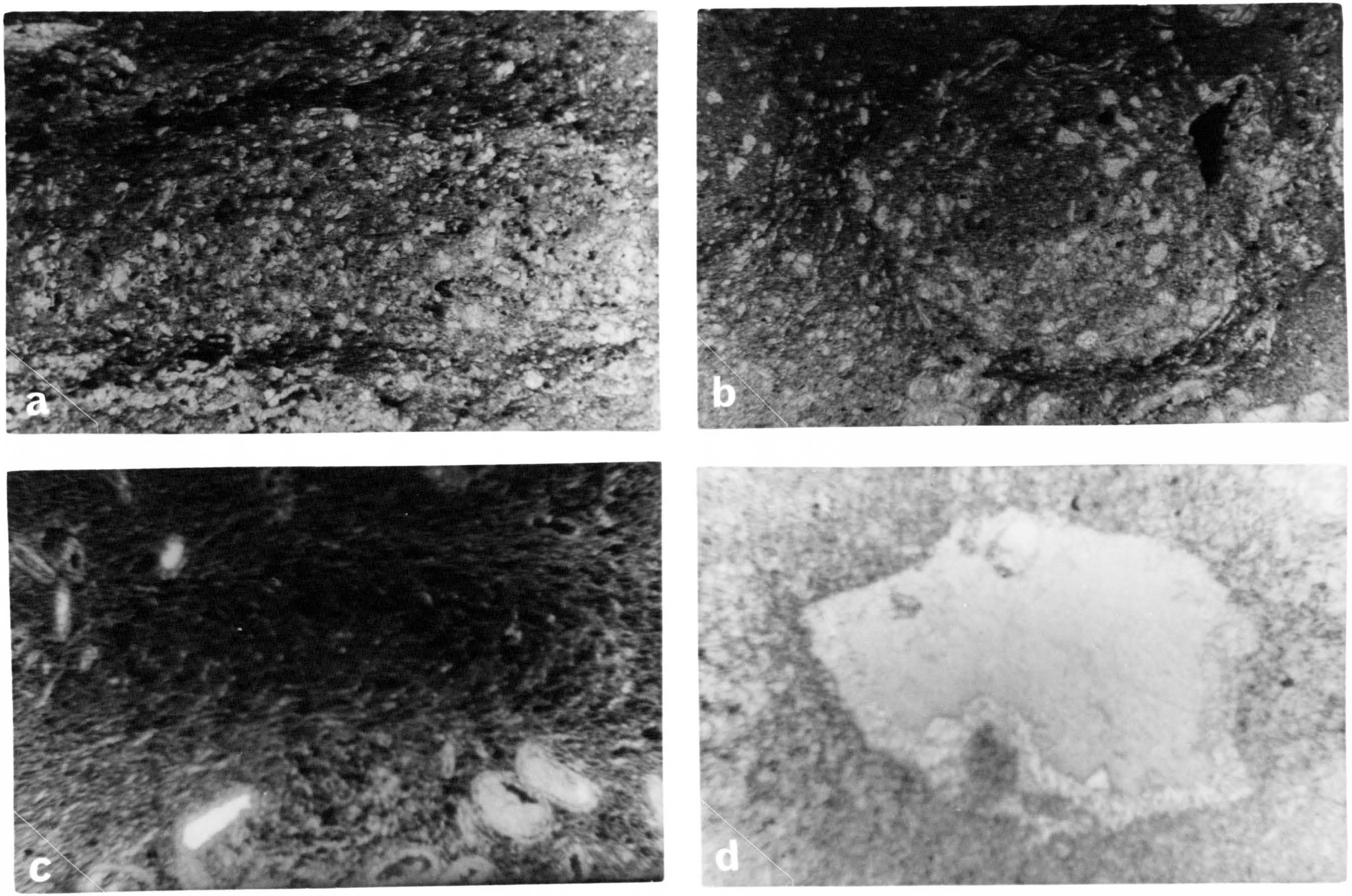


PLATE 15

partially filled (plate 15d). The fillings may be structured or structureless. Concentric or 'spreiten' type structures (plate 15c) are usually preserved through the inclusion of coarser grained material such as ooliths, shell fragments, or angular quartz fragments, frequently pseudomorphed by clear colourless siderite (plate 15ab) (pages 226). Elsewhere these structures are preserved through the disposition of diagenetic siderite in such a manner as to indicate that sideritisation and burrowing were taking place simultaneously.

b) External fabrics created through the interrelation of pore spaces with matrix occur in grainstones and packstones as a result of mud filtering and/or winnowing. The original relationship between mud rich and grain rich facies is difficult to assess on the small scale because, except in crossbedded oolite where thin chamosite mudstone layers are found interbeddėd with oolite grainstone, primary bedding structures have been obliterated through the activity of the infauna. Fabrics attributable to mud filtering are therefore rare; only in a very few grainstone thin sections (Two Foot Seam) can the presence of intergranular mud be interpreted as the result of filtering rather than of burrowing.

On the other hand winnowed fabrics are common in some high energy deposits. In crossbedded oolites from the Main Seam the margins of mud-filled burrows were sculptured with lobes presumably as a result of the passage of water through the intergranular voids, possibly aided by attrition between the neighbouring grains, during early burial. Carried to extremes this process leads to mud collapse (plate 16c) and to the

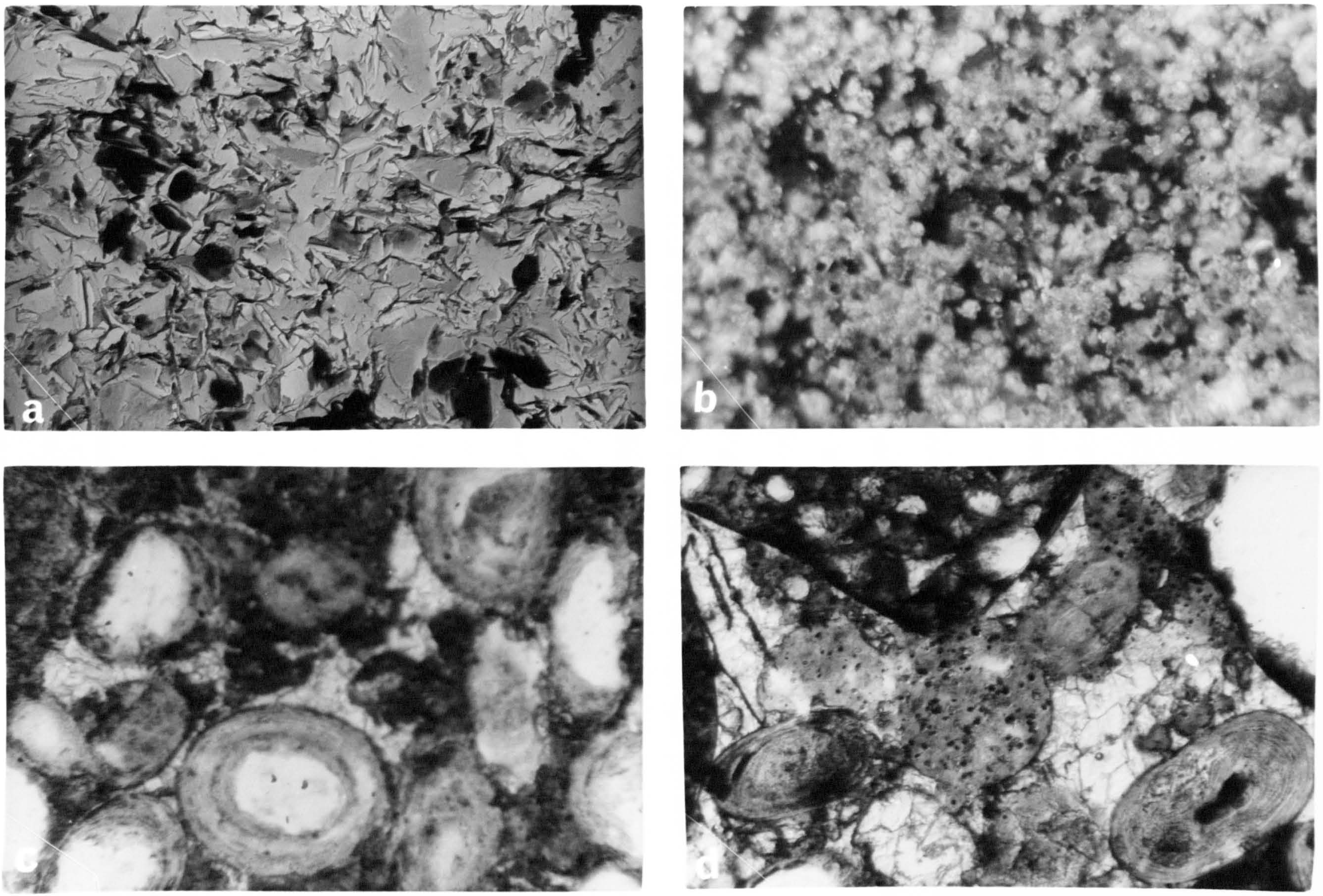


PLATE 16

formation of grains of matrix (plate 16d). It is indicative of fairly vigorous erosion and transportation within the pores. The cohesiveness of the mud may be explained by the presence of algae within these muds (page 124) but the protuberences themselves are free of any sign of algal encrustation.

The process of sediment winnowing appears to be of particular importance in the development of fabric in local intrabasinal sediments such as ironstones. In particular Dunham (1962) has emphasised the importance of "currents of removal" over "currents of delivery" in the deposition of limestones. For the accumulation of mud, periods of calm water and incomplete winnowing are required. Although the presence of burrows undoubtedly contributes towards fixing the mud in the ironstones, it must be remembered thatthe very existence of an infauna presupposes intervals of calm water. In the matter of mud content and infauna the Cleveland chamosite oolite shoals are quite distinct from recent aragonite oolite shoals where the shifting nature of the bottom precludes both mud and infauna, (Purdy 1964, p. 254). However, how far this indicates redistribution of and mixing of the sand and 'mud' fractions and how far it may be taken to show that a quieter overall environment of deposition prevailed in the Cleveland oolites is difficult to say.

4. Conclusion

It is concluded thatthe primary matrix of the Cleveland Ironstones consisted of a mixture of chamosite with various percentages of terriginous quartz and clay mineral and that chamosite was in fact forming by the halmyrolytic breakdown of this terriginous material (pages 149 & 315-317). At the time of burial the process of conversion was almost complete in the chamosite packstones but only partially completed in the wackestones and mudstones. Siderite, although formed during early diagenesis, both at the expense of chamosite and terriginous material, appears to indicate the continuation of the same process of iron enrichment after burial.

B. PRIMARY POROSITY

Although, because of cementation very little of the primary porosity is retained by the ironstones, it may be readily estimated in thin section, except where extensive spastolithisation occluded the pores before the deposition of cement. Two types were counted during modal analysis; intragranular and intergranular porosity. Secondary porosity was specifically excluded and no estimate was made of submicroscopic porosity.

1. Intragranular porosity occurs because of the presence of chambered (ammonites, gastropods, foraminifera) or articulated shells (brachiopods, lamellibranchs, ostracods). Of these the first group is the more important. Articulated lamellibranchs and brachiopods often gaped sufficiently to allow the ingress of mud (e.g. the burrowing forms) and only occasionally in coquinoid lenses did they remain open until the time of cementation.

Volumetrically original intragranular porosity was by far exceeded by original intergranular porosity, (> 95%).

2. Intergranular porosity is most important because it indicates the capacity of the environment to separate coarse grains from fine by the process of winnowing. It is this capacity which is one of the bases for the Dunham/Folk limestone classifications.

The relationship between intergranular porosity, matrix and grains in the Main and Two Foot Seams is shown in figures 34a and 34b. Both figures indicate the way in which intergranular porosity increases with grain percentage. In the mudstones it is nil, but rises steadily in the wackestones and packstones reaching a maximum in the grainstones. The most important difference between these diagrams is the value of this maximum and thus in the position of the spar limit line. In the Main Seam the observed maximum was 26.2%, in the Two Foot Seam 42.2%. Part of the difference arises through the absence of grainstone facies from the Main Seam. However, even if the matrix were removed from the totally grain supported fabrics (open circles) the maximum would only reach about 38%, while the same adjustment to the readings from the Two Foot Seam would raise the maximum to about 54%. More importantly the difference arises because of the geometrical properties and packing of the grains in each case. If ooliths are likened to spheres a variety of types of packing are possible ranging from loose (48 percent void) to close packing (26 percent void). However, in sediments loosely packed configurations of spheres tend to be unstable, so that it is not surprising to find that under optimum conditions in the Main Seam the ooliths approach close packing (grain limit 72-73 percent). Not so in the Two Foot and

Raisdale Seams, where, as the ooliths become more discoidal, looser grain configurations are stable (grain limit in the Two Foot Seam 65 percent). A further factor in these seams is the occurrence of bladed shell fragments, which allow even looser packing. The presence of grains in excess of 74 percent may usually be interpreted as the result of overpacking,(spastolithisation), during compaction, but occasionally, in poorly sorted rocks, a slight overestimate of grain percentage is involved.

The shape of ooliths in ironstones may have important implications upon their value as ores. The more discoidal the ooliths become the greater is the possible pore space available for the precipitation of siderite spar. Other things being equal, therefore, the Two Foot and Raisdale Seams have the potential to produce richer ores than the Main and *Avicula* Seams. However, in the past it has been found that this advantage is more than compensated by the inferior thickness of these seams.

V DIAGENESIS (PART 1)

A. COMPACTION

The tendency of compaction in sedimentary rocks is to reduce porosity by tightening the packing of matrix and grains, thereby incidentally excluding pore water. This always involves reorganisation of the depositional fabric, and often deformation to the constituents; in the matrix mainly by flowage, in the grains and cement (if present) mainly by breakage. It may also involve pressure solution.

1. Deformation fabrics in the matrix

Several fabrics are attributable at least in part to the deformation caused by compaction. The first is the preferred orientation among the clay minerals, which is particularly well developed in some chamosite mudstones (e.g. in the green~~stone~~ facies of the ~~Black Hard~~ Blue Mottle) as well as in the shales associated with the ironstones ~~(pages ——————)~~. Under polarised light whole slides extinguish almost uniformly when bedding is parallel to the nichols. Although partially a depositional feature the perfection of this orientation is undoubtedly attributable to compaction.

A second fabric occurs in the presence of early diagenetic siderite. During its growth this siderite picked out flow lines in the matrix which are believed to have developed during compaction (plate 15c). The amount of compaction possible in the mudstone and wackestone facies is clearly influenced by the amount of siderite and its rate of growth, since the mineral occludes the pores and eventually produces a framework resistant to compaction. In the Two Foot Seam in Rosedale brecciation and veining occurs where interburrowed siderite muds have undergone differential compaction ~~(plate)~~. This process appears to take place because of different growth rates in the siderite. Thus a sediment which is lithified early by the completion of a siderite framework may be ruptured to accommodate further compaction in surrounding sediment.

Thirdly deformation may be detected in the distortion of burrows and especially open burrows.

Deformation ~~to~~ of the matrix occurs most obviously in mudstone and wackestone facies which lack grain support. With the possible exception of the last none of these fabrics can be used to give a quantitative assessment of the amount of compaction accomplished. In some recent muds a volume reduction of up to eighty percent may take place merely by the expulsion of pore water. Part, although not all the variation in thickness between grain rich and grain poor facies may be ascribed to differential compaction, however. It may be that this variation would be greater but for the presence of diagenetic siderite.

2. Spastolithisation

The term spastolith was introduced by Rastall and Hemingway (1940, p. 265) to describe deformed ooliths. Spastolithisation is therefore a special type of grain deformation, occurring quite commonly in oolitic deposits and especially in oolitic ironstones.

It is a characteristic feature in all the Cleveland Seams.

a) <u>Nature of deformation</u>

The deformation in the present ooliths appears to be either plastic, or brittle, or plastic and brittle, depending upon the tenacity of the ooliths. Where the deformation is plastic ooliths are extruded into the intragranular voids, and may assume the most complex shapes without rupturing (plate 18). By contrast brittle deformation leads to fracturing and invagination. In the simplest case the oolith is penetrated by a single flap of ruptured laminae, but more complex forms broken at several sites, or with displaced polar surfaces, are also common ~~(fig.)~~. In a favourable section, this kind of spastolith may be recognised by its hook like apophyses (plate 17a).

Since the tenacity of the ooliths presumably depends upon the progress of diagenesis within the oolitic envelopes, it is concluded that plastic ooliths are less mature than brittle ooliths which have undergone hardening, perhaps due to slight recrystallisation, or to replacement by siderite (pages 219-221) or some other mineral.

Combinations of plastic and brittle deformation within one oolith are very common. Frequently while the outer laminae rupture, the core (i.e. nucleus and inner laminae) deforms plastically. This may be explained by advance diagenetic hardening at the outside of the oolith, but is more likely to be correlated with the

PLATE 17 Spastoliths

a) Simple chain. Main Seam, North Skelton.

b) Chain with fractured siderite spar. Main Seam, North Skelton.

c) Complex chain. Two Foot Seam, Staithes. Note: Spastoliths retain chamosite, non deformed ooliths replaced by calcite.

d) Stylolitic spastolith chain. Raisdale Seam, Hawsker.

x ~~200~~. 70

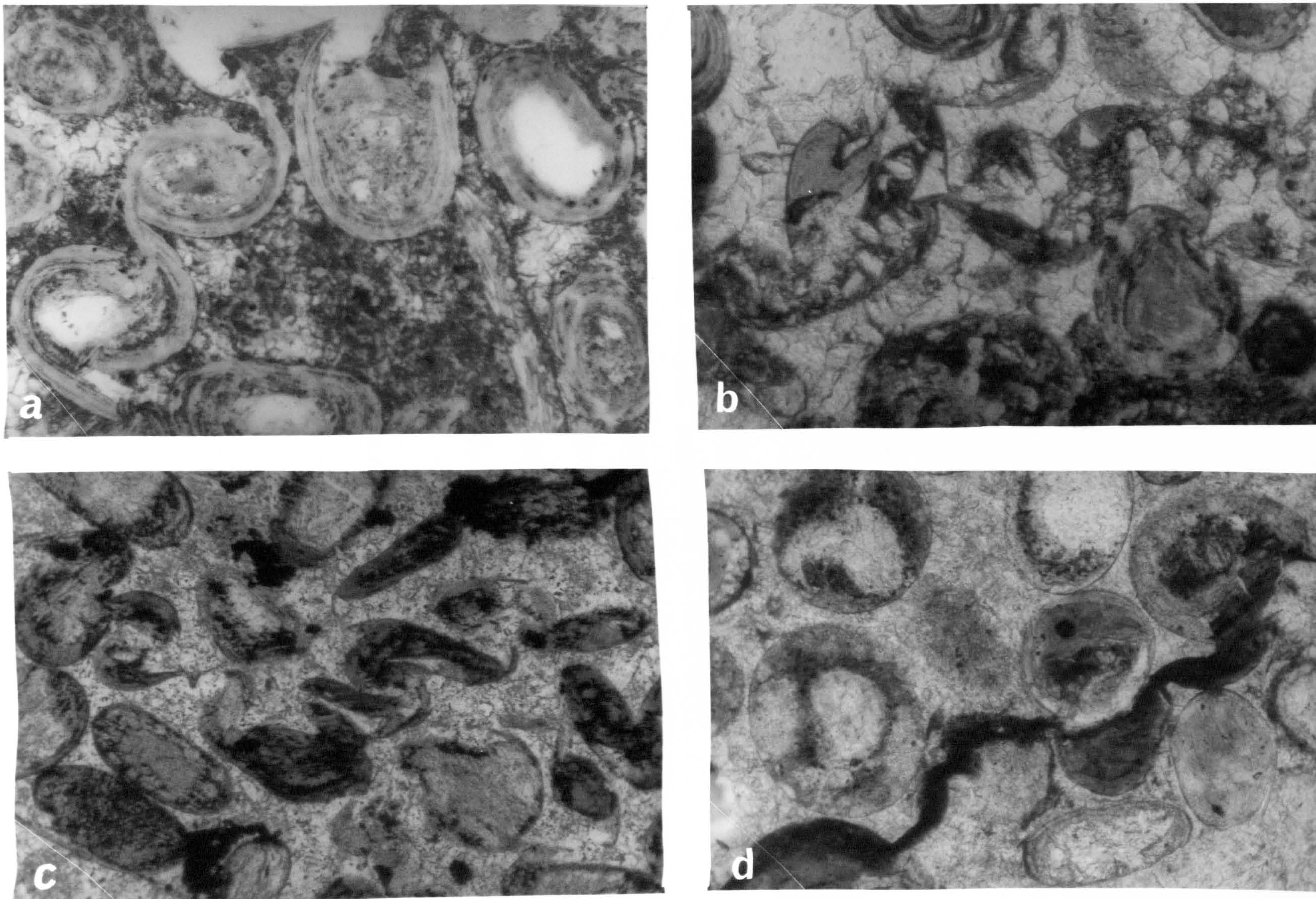


PLATE 17

predominance of orientated chamosite in the outer laminae, which because of superior packing is less competent than the unorientated chamosite of the core. Furthermore it must be remembered that the enclosing laminae around the core have a retaining effect upon it, preventing serious rupture.

Despite the variety of forms produced all indicate the operation of compressional stress. No 'V' shaped cracks of the type described by Carozzi (1961), presumably attributable to tensional stress, are found.

b) Association with normal ooliths

Spastoliths occur singly, surrounded by undeformed ooliths, in chains and sheets ramifying normal oolite, or in lenses and layers (plates 17 & 18). Among the brittle ooliths every transition exists between single spastoliths, chains and sheets linked together by the spastolithic apophyses, and the layers and lenses of total spastolithisation. With each step in this morphological series the deformation to both ooliths and rock fabric increases. No such series is found among the plastic ooliths which occur only in layers and lenses.

Spastoliths occur in all the oolitic facies but the style varies depending on the nature of the grain support. Single spastoliths, chains and sheets are the common forms in packstone facies, while total spastolithisation is mainly restricted to grainstone and wackestone-mudstone facies. The nature of the rock framework also influences the orientation of the planar spastolithic structures. A strong preferred orientation parallel to the bedding is typical of wackestones and mudstone, but less common in grainstones and packstones except where spastolithisation is total.

c) Time of deformation

In the case of the Cleveland ironstones the time of deformation can be fixed fairly closely. It apparently began when at least some of the ooliths were still plastic and yet when a rock framework was already in existence. The course of spastolithisation is controlled by the nature of this framework, and therefore it is unlikely that current action was involved, rather a stress capable of being transmitted through the sediment. Thus deformation continued during early diagenetic hardening of the ooliths and even after marginal replacement by siderite, which may be demonstrated to have taken place after burial (page 224).

The process was generally halted when the grain frameworks were reinforced by the precipitation of a mineral cement, but in some grainstones (e.g. in the top block of the Main Seam) continued even after cementation leading to brecciation in the cement and further rupturing of the ooliths (plate 17b).

Spastolithisation also occurred concurrently with the development of early diagenetic aragonite concretions (in the Two Foot, Raisdale, and Avicula Seams) (pages 181-184). Here total

PLATE 18 Total spastolithisation

a) Oolite grainstone. Main Seam, Kettleness.

b) Oolite wackestone. Main Seam, Staithes. (White oolith is replaced by kaolinite).

c) Complex deformation. Two Foot Seam, Ayton Mine.

d) Total spastolithisation. Avicula Seam, Staithes.

x ~~260~~. 70

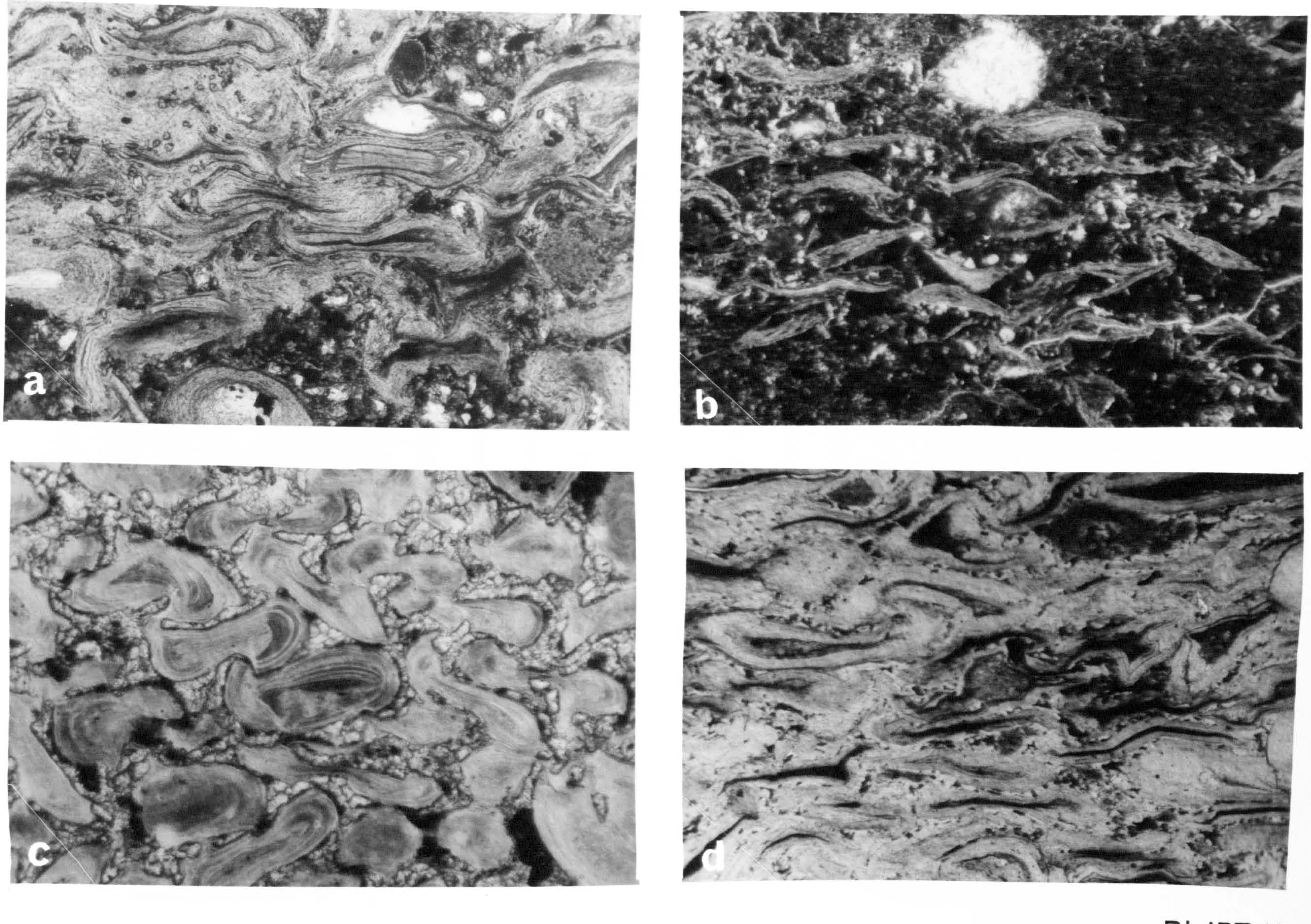


PLATE 18

spastolithisation occurs outside the concretion, while only mild collapse occurs within ~~(Fig.)~~.

d) Mode of deformation

Only one type of stress fits the requirements of time and fabric: the stress induced by compaction. The manner in which the morphological series described previously is thought to arise, is described below.

(i) Single spastoliths, occurring only in grain supported fabrics are thought to indicate the position of weak spots in the grain frameworks either inherent within the ooliths, or resulting from the accummulation of strain due to uneven packing. The deformation to the oolith is small, and the collapse of the framework does not spread, indicating rapid dissipation of the stress.

(ii) If this stress is not dissipated but transferred to neighbouring ooliths the collapse of the framework may spread in a series of spastolithic chains and sheets. The degree of deformation is often more severe than in the single spastoliths, because of the concentration of stress along the newly produced lines of weakness. The configuration of these lines depends on the relative disposition of matrix and grains. In the grainstones and packstones stress is transferred directly through the grains so that the vertical stress induced by compaction is dispensed equidirectionally leading to the development of a three-dimensional network of spastolithisation. However, with increasing mud content less and less stress is dispensed by the grains, until finally in the wackestones and mudstones the whole unidirectional compactional stress is transferred through the mud so that excepting the presence of major inhomogeneities in the matrix, such as might be produced by burrowing, the spastoliths tend to develop parallel to the bedding.

A most interesting feature in both sheets and chains is the way in which the spastolithic apophyses become linked together (plate 17). According to Carozzi (op. cit.) this linkage takes place on the sea floor by current action, but from the observations above it seems much more likely to have been a post-depositional effect.

(iii) With continuing stress the grain framework may be completely destroyed and total spastolithisation results. This occurs most commonly in grainstone and mudstone, wackestone facies, so that it must be assumed that strain was at a maximum under these conditions; a grain framework with some mud support, therefore appears to offer the most resistance to compaction.

Total collapse probably commenced in the weaker plastic oolites, particularly where mud support was lacking. Apparently once initiated in this type of situation it proceeded rapidly towards total deformation, for plastic ooliths usually occur in layers and lenses.

Total spastolithisation is particularly common in grainstone facies within the top few inches of several seams (Main, Two Foot, Raisdale, and *Avicula*) where it appears to coincide with the presence of either plastic or slightly brittle ooliths. This is taken to indicate that diagenesis had not advanced sufficiently to harden these ooliths against collapse, at the time the seams were buried by newer deposits. In the case of the Two Foot, Raisdale and *Avicula* Seams this sediment was deposited within the same ammonite subzone as the seam itself, but this does not seem to have been the case in the Main Seam.

e) Results of spastolithisation

Spastolithisation offers the main outlet for the stresses induced by compaction in the grain rich ironstones. In the individual ooliths both deformation, in the forms described above, and compaction results. The latter is accomplished by tighter packing in the oolitic envelope and an improved preferred orientation among the component crystals, which raises the birefringence into the high first order. The resistance of the ooliths to alteration is thereby increased, so that even after extensive replacement by calcite, for example, chamosite may be preserved in the spastoliths.

In the rock as a whole the pore space is partially or completely occluded, hindering the passage of pore water and restricting the volume available for the precipitation of siderite spar, hence lowering the grade of the ironstone.

The total loss in volume to a rock as a result of spastolithisation may be as much as 85 percent ~~(fig. —)~~, but taken through a seam as a whole it probably averages 10-15% percent. Assuming a compaction of this order the present 9'6" of ironstone in the Main Seam at North Skelton Mine may be said to represent between 10'6" and 11'0" or original sediment.

3. Pressure Solution

Intergranular corrosion resulting from pressure solution is a rare phenomenon in the Cleveland Ironstones. However occasional examples of incipient stylolitisation have been observed in the Main, Two Foot and Raisdale Seams often developing along lines of spastolithic weakness, because of renewed stress following cementation (plate 17d).

B. SHRINKAGE AND SOLUTION-COLLAPSE

The development of secondary porosity in the ironstones gives rise to a further source of weakness in the rock framework and to another type of deformation structure. Whereas during compaction it is the weight of overburden which causes the instability within the rock frameworks, in this case it is the weakening of the grains themselves which is responsible, so that while compaction may encourage collapse it is not the essential factor. Deformation may be of two kinds which will be referred to as internal or external collapse. Internal collapse takes place without change to the mould shape; in other words no compaction has taken place. By contrast during external collapse the mould itself is deformed and the cavity is transferred beyond the initial void.

The origin of the secondary porosity may be either physical (shrinkage) or chemical (solution, or volume changes following replacement) and it is not always possible to isolate the cause in each instance.

1. Shrinkage and Solution in Ooliths

Many ooliths reveal internal discontinuities and deformations which are neither original nor the product of compaction. The simplest examples are the small cavities formed by the withdrawal of one oolitic lamina from another, or from the periphery of the oolith. Such cavities, now infilled with mineral cement, are unlikely to have been an original

PLATE 19 Collapsed ooliths

a) and b) solution collapse in ooliths

from Main Seam, North Skelton.

Void filling quartz.

x ~~900~~. 300

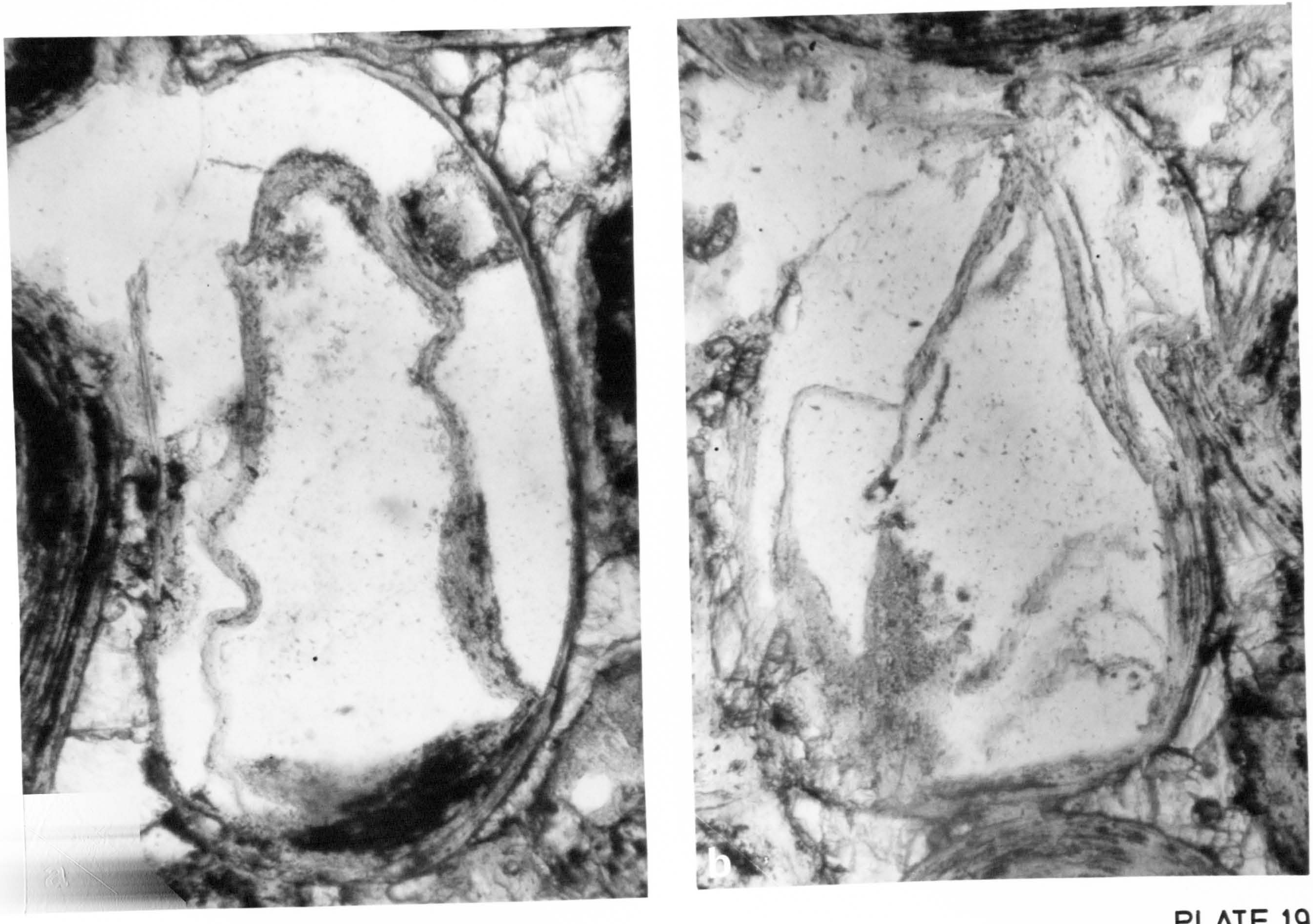


PLATE 19

feature of the ooliths (they do not occur in recent aragonite ooliths) and are therefore presumed secondary in origin (plate 21d). Some marginal cavities appear to have been transferred from the interiors of the ooliths, but as a rule the cavities are too small to involve collapse. In these cases there is no evidence of mineral having been removed and the loss of volume to the ooliths is small (less than 10%). The most likely cause is therefore shrinkage resulting from dehydration or from the decay of organic matter held within the envelope. Although the discontinuities between the oolitic layers of algal ooliths are somewhat larger and give rise to characteristic collapse structures (plate 10a), once again there is no evidence of mineral matter having been removed, and therefore the volume loss is attributed to shrinkage. The greater size may be correlated with a higher content of organic material.

Significantly the loss of volume is always taken up between the laminae, or between the periphery of the oolith and the mould. Shrinkage cracks of the type developed in glauconite grains occur only rarely in the nuclei of superficial ooliths and never in the oolitic envelopes.

However, in some collapsed ooliths, and particularly in the packstone facies of the Main Seam, it is clear that mineral matter has been removed in order to form the cavities; completely hollow ooliths in which one or more layers have been selectively removed, occur alongside normal ooliths. Even in layers which have been largely eliminated relics may remain and indicate that the loss is mainly at the expense of the unorientated chamosite of the envelope and sometimes of the nucleus as well (plate 19). The number and thickness of missing layers varies depending upon the distribution of orientated and unorientated mineral in the original oolith, but as a rule only one or two are absent. Those parts of the oolith which have resisted removal, mainly the nuclei and layers consisting of orientated chamosite laminae, exfoliate and slump towards the base of the cavity in varying degrees of contortion, depending upon the foreshortening of the layers and upon the cleanness with which they break away from the periphery of the oolith (plates 19a, b).

No compaction is involved in these cases, the layers having slumped and exfoliated entirely under their own weight. Clearly more than shrinkage is involved. Rather the ooliths appear to have been selectively dissolved, presumably by the passage of acid solutions. The surprising feature is the way in which these solutions have picked out the less resistant parts of the oolitic structure. Comparable collapse phenomena have been described by Carozzi (1963) under the name 'half moon' ooliths (Wherry 1916) but the original minerals in this case are thought to have been calcite and anhydrite or gypsum, the solution of the sulphate being responsible for the collapse and deformation. There is no suggestion in the Main Seam ooliths of any mineral other than chamosite having been present.

The majority of these secondary voids, and particularly the solution cavities, are infilled with late void filling spars such as calcite and quartz (see pages 185-189, 191) but the smaller shrinkage cavities often contain siderite spar, an early void filler. In consequence shrinkage classifies mainly as an early diagenetic effect, solution as a late effect (pages 260-262).

Solution collapse phenomena are especially common in ooliths which occur in the vicinity of organic burrows, from which it appears that the burrows may have been the source of the acid solutions responsible for the solution of chamosite. However, because the cavities were not formed until after cementation (i.e. they are late diagenetic) the burrowing animals cannot have been directly responsible. Either the burrows acted as channels for percolating solutions or the acids developed within the mud infillings, possibly due to the decomposition of organic material during diagenesis. Since there is no reason to suppose that the burrows were more porous than the surrouding sediment even following cementation, the latter alternative seems the more likely.

2. <u>External collapse and the behaviour of siderite rinds following solution</u>

External collapse is rare in the small cavities formed by shrinkage and solution in ooliths, but is common where larger grains have undergone solution. Aragonitic shells are particularly prone to solution and external collapse, but intraclasts may also suffer to a lesser extent

especially following intense sideritisation (pages 222-223).
However, similar collapse structures may also arise in the latter without solution apparently taking place; simply as a result of compaction (plate 20c)

The extent to which these moulds collapse varies. In some cases shell cavities were completely closed before a supporting spar could be precipitated (plate 21a), but as a rule the collapse is less severe and the loss in volume to the cavity small.

During collapse the mould frequently ruptures and fragments of the wall protrude or fall loose within the cavity later to be preserved in the void filling mineral. The most common intruders are fragments of siderite coronas (page 178) and contical siderite replacement rinds (page 224), but occasional ooliths and fragments of matrix occur.

The siderite rinds behave in much the same way as the micrite envelopes of Bathurst (1964, p. 365) in limestones. They resist solution, become ruptured, separate from the mould wall, and then are either pushed into the cavity or intrude under their own weight (plates 21b, c). Despite their apparent fragility it is unusual to find rinds which are completely detached from the margins of the moulds. Where compaction has continued it may be possible to estimate the foreshortening of the mould from the length of rind.

3. Pinch and Swell Structures

The name pinch and swell is used to describe a peculiar group of structures, which develop through the solution and compaction of

PLATE 20 Shell collapse

a) Internal collapse of aragonite lamellae in shell from Two Foot Seam, Glaisdale.

b) Pinch and swell structure affecting both internal and external shell structures. Note spar breakage.

c) Pinch and swell between ooliths and mudstone intraclast.

d) Pinch and swell structure between former aragonite shell and chamosite ooliths.

x ~~100.~~ 70

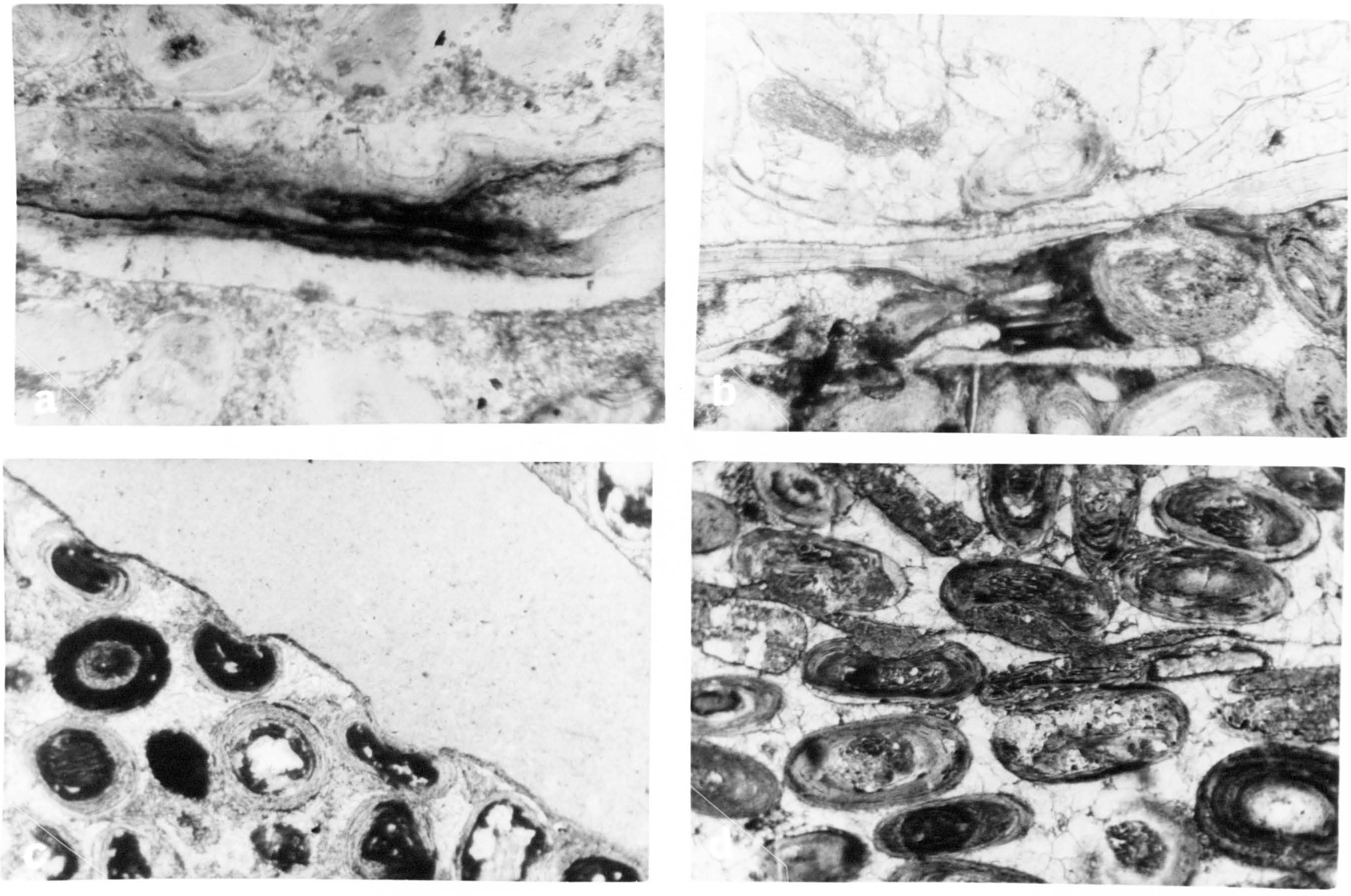


PLATE 20

shells, which are presumed to have been aragonitic originally (pages 135, 140). The structure involves both internal and external deformation fabrics which will be described separately.

a) Internal effects

Solution collapse is a common feature in shells, not only from the Cleveland Ironstones but from a large number of limestones (Bathurst 1964, p. 369). However, normally the removal of shell material is completed before the introduction of void filling spar, so that it is unusual to find evidence of collapse and internal structure in the same shell. In the Cleveland Ironstones the solution of aragonite shells sometimes appears to have been selective in the same way as the solution of ooliths, and lamella structures, now relict by dusty inclusions in replacement calcite, have sometimes undergone slumping and contortion (plate 20a). Although some of these deformities might be explained by malformation of the shells, they are in fact far too common in some thin sections to be dismissed in this way. The dusty inclusions probably represent the position oforganic rich (nacreous) layers, which resisted solution and collapsed following the removal of more soluble material.

While in this condition the shells were especially liable to compaction, uneven pressure leading to constriction both of the mould walls and internal structures (plate 20b). The deformation is normally plastic rather than brittle and suggests that the interior of the shell wall was in a spongey condition at the time of compression.

PLATE 21 Collapse structures

a) Shells completely closed by solution collapse prior to cementation by siderite. x ~~200~~. 70

b) Ruptured shell and siderite rind following solution collapse. Void filling quartz. x ~~100~~ 30

c) Former aragonitic shell showing both external collapse, void filling, and yet with internal relict lamella structure.

x ~~100~~. 30

d) Minor shrinkage collapse in ooliths. Two Foot Seam, Ayton Mine. Void filling - calcite. x ~~200~~. 70

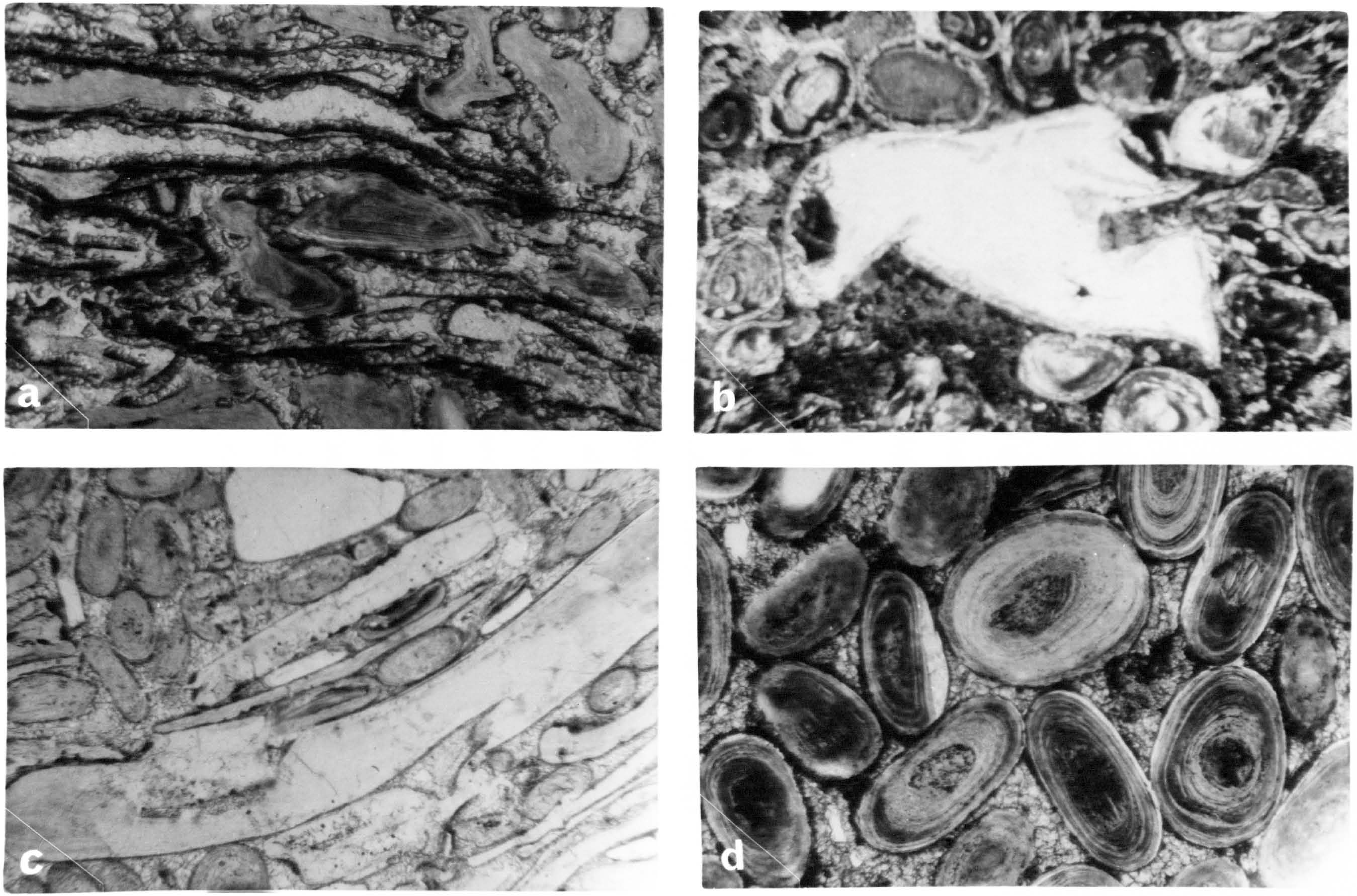


PLATE 21

b) <u>External effects</u>

Shells which have undergone this kind of solution-collapse pinch and swell in the most surprising manner, especially if an ornamentation of ridges was present, as for example in <u>Astarte</u>. The constrictions are therefore a function, in part, of the amount of pressure applied to different parts of the shell wall, and in part of the original shell morphology. The effect is most severe in thin walled shells; less common and less pronounced near the hinges and in thicker shells. Thus in a shell 150 μ in thickness the reduction in the width of the shell wall may be in the ratio of up to about 25 : 1 in a length of about 300 μ, while in a shell 600 μ thick up to 3 : 1 in 1200 μ.

However, pinch and swell is also affected by the nature and resistance of the mould wall. For example the relative resistance of shells, ooliths and siderite spar varies.

In some cases ooliths cause constriction but in others shells swell at the expense of ooliths and pinch against siderite spar (plate 20d). Rather surprisingly the latter has also been observed where ooliths and spar lie adjacent to an intraclast (plate 20c), but since no solution is apparent this is regarded as entirely a compactional phenomenon. However, the mechanism appears to be the same in both cases: during compaction partly dissolved shells, and intraclasts may be deformed by pressure from the siderite cements but retain sufficient strength to intrude adjacent ooliths. Instances in which siderite spars intrude ooliths have been described previously (pages 159).

c) Time of formation

Although some shells underwent solution, collapsed and were compacted before the deposition of siderite spar (pages 168) the majority of solution cavities, not only in shells but in all the constituent grains, formed after the emplacement of the siderite cements. Hence siderite is involved in the production of pinch and swell structures, is brecciated following collapse and occurs along with other debris in ruptured shell moulds.

4. Shrinkage Effects in the Matrix

Secondary voids which could be attributed to solution do not occur in the matrix of any of the ironstone seams. However, there may on occasion be evidence of volume loss by shrinkage. For example in one or two places in the Main Seam chamosite mud appears to have withdrawn from grains which it originally enclosed leaving cavities which surround and mirror the grain shape. Such cavities are early diagenetic in origin and contain siderite spar. It is probable that the "outer layers of siderite in parallel growth" on siderite rinds said by Hallimond (1925, p. 22) to be "rounded by transport" are of this type.

Elsewhere, in the sideritic facies of the Main and Two Foot Seams septariate cracking has taken place following the differential

growth of siderite associated with burrows (pages 213)
These cracks are possibly of later origin than the shrinkage effects, being infilled with kaolinite, a late spar (plate 36b , page 239). In neither of these cases has the loss in volume been sufficient to cause collapse.

5. Conclusions

Secondary porosity in the Clëveland ironstone seams arises mainly as a result of solution, but also through shrinkage, and occasionally through replacement. Shrinkage is mainly an early diagenetic effect, preceding cementation, and forming small cavities in ooliths and matrix which are only rarely subject to collapse. The loss in volume to the ooliths is small and does not favour the supposition that they were incorporated in the sediment in a colloidal state. Had this been the case larger septariate structures might have been expected rather than small concordant partings.

Solution is effective only within the constituent grains and creates larger cavities which are liable to both internal and external collapse depending upon their size. External collapse is commonin large moulds (mainly shells), rare in the smaller oolith moulds; internal collapse occurs only in ooliths and shells.

Where the criteria for void fillings are suspect, as for instance, in the case of random calcite spars pseudomorphing aragonite shells (pages 187-188) collapse structures give important evidence for the existence of a cavity or partial cavity stage. Relict internal textures are usually acceptable evidence of 'in situ' replacement, especially in shells, but the occurrence of internal collapse phenomena in ooliths and shells indicate that external collapse may occur without the complete removal of the internal textures of ooliths or the micro-structure of shell walls. The emplacement of the pseudomorphic mineral therefore probably takes place by a combination of replacement and void filling both on the large and small scale (See for example ~~figure~~ plate 21c).

C. CEMENTS AND DRUSY SPARS

1. General Statement

Crystals and mosaics precipitated from solution within the voids of sedimentary rocks are referred to as cements and drusy spars (eospars of Nichols 1967) in contradistinction to the spars produced by recrystallisation (neospars) and replacement. The cement or intergranular spar is that part specialised in binding the constituent grains, while the drusy spar occupies intragranular voids or moulds and vugs developed secondarily during diagenesis (Bathurst 1958).

With particular reference to the calcite spars of limestones Bathurst (1958, 1959a, 1959b, 1964) has been foremost in attempting to provide criteria by which void filling spars may be recognised from those produced by recrystallisation and replacement. The distinction is made first on gross morphology and second on the evidence of grain morphology (Bathurst 1958, 1964).

In the course of this work a variety of mineral spars have been recognised each characterised by different crystal fabrics, in part dependent upon mineral habit, and in part upon the conditions of deposition. Some are sufficiently distinctive to be immediately recognisable as void fillers, while others are only with difficulty, or not at all, separable from replacement spars. In practice the identification of primary void fillings proved straightforward, both from the evidence of gross morphology, and grain morphology (Bathurst 1958, 1964, Stauffer 1962, p. 362), but the evidence for secondary void fillings was often equivocal. Particular difficulty arose in distinguishing between replacement and cavity fillin pseudomorphs after skeletal grains, which are touched upon briefly in this section before being treated in detail (pages 248-250).

2. Descriptive Terminology

The descriptive terminology adopted here is based on that of Folk (1965) ~~(see Table)~~. The most important feature of this scheme is the distinction made between corona spars (overgrowths and crusts) on the one hand and random spars on the other; between those spars which are related crystallographically or physically to the constituent grains and those which are not. When dealing with mosaic spars (polycrystalline overgrowths and crusts) the term random should not be applied in the presence of the following corona fabrics (Bathurst 1958):-

(i) Preferred orientation of optic or long axes of crystals normal to growing wall.

(ii) Continuous increase in grain size away from the growing wall.

(iii) Protrusion of large number of small grains into a smaller number of large grains in a direction normal to the growing wall.

The Folk scheme (1965) is qualified by an assessment of grain size and shape and a code for each spar type is provided.

3. Sequence of precipitation (~~Table~~ Fig. 38)

In those ironstone seams which show clear evidence of a primary or secondary porosity the spar fillings may be divided into two stages designated here for convenience as:-

(i) early spar,

and (ii) late spar.

Siderite and aragonite are the only two minerals which fall in the category of early spar. They always develop as coronas, and are almost entirely restricted to primary intergranular and intragranular voids.

Late spars include calcite, chalcedony, sphalerite, barytes and possibly kaolinite, mainly restricted to secondary voids and occurring exclusively in random plates and mosaics. Of these only calcite occurs commonly in primary voids and then only following siderite and aragonite.

This distinction of fabric and mineralogy holds in every seam where these minerals occur as sparry fillings (Main, Two Foot, Raisdale and Avicula), and finds its equivalent in replacement spars also. ~~(page)~~. The petrographic evidence does not favour the supposition that the mineral species were deposited simultaneously in each seam, and therefore this appears to be a case of parallel diagenesis (pages 256 - 262).

4. Siderite (Chalybite)

The most important void filler both from a quantitative, and from an economic point of view, is siderite. In hand specimen it is golden brown in colour, but clear and colourless in thin section except when weathered. This is in marked contrast to recrystallised siderite muds which usually contain cloudy crystals and replacement spars which retain

a golden yellow colour even in thin section (pages 217 - 225
Measurements made on crystals from intergranular voids in the Main Seam mainly yield values for ω of between 1.81 - 1.82, closely similar to those obtained for siderite from the Northampton Sand Ironstone (1.81 - 1.83) (Taylor 1949, p. 49) and the Marlstone (1.785 - 1.807) (Edmonds et al. 1965, p. 68), which have been interpreted as indicating the presence of $CaCO_3$, $MgCO_3$ and $MnCO_3$ in solid solution.

a) The Mosaics

Siderite occurs ubiquitously in mosaic fabrics both as crusts and polycrystalline overgrowths; if early diagenetic siderite replacement rinds are present on the constituent grains syntaxial overgrowth takes place, if not crusts develop. Monocrystalline overgrowths do not occur. The crystals are equant to bladed and vary in size between about 20μ-200μ; they show uniform or slightly spectral extinction. The cause of the latter is not known but is an original effect recorded from a number of spars, and not the result of post-depositional straining since these rocks are undeformed. As pointed out by Bathurst in his discussion of radiaxial mosaics the value of grain morphology for the diagnosis of void fillings is greatly reduced in grains which show undulose or spectral extinction (1959b, p. 511, 1964, p. 359). However, in the present case the distortion is small (cf. calcite, pages 186-188) and these spars are closely analogous to Bathurst's para-axial calcite spars (Bathurst 1964, p. 359). In view of the complete variation which exists between distorted and undistorted crystals the author prefers not to use Bathurst's two-fold division into para-axial and radiaxial mosaics. The following are the criteria which may be applied for the identification of siderite cement and cavity-fill.

(i) It occurs principally in the intergranular spaces of grain supported ironstones.

(ii) It shows cavity forms and may develop dog-tooth or nail-head spar.

(iii) It develops distinctive polycrystalline coronas (plate 22b).

(iv) The presence of true crystal faces and compromise boundaries leads to straight, or if the crystals are distorted, slightly curved intergranular boundaries (plate 22a).

(v) Crystal size increases towards centre of cavity (plate 22a).

but (vi) Enfacial angles (Bathurst 1964, p. 362) are only poorly developed possibly due to crystal distortion.

Exactly similar mosaics, showing relict internal shell structures, have been observed from siderite pseudomorphs after aragonite shells (see pages 225 - 226 and Folk 1965, p. 44), but excepting these cases, very little difficulty arises in the recognition of these spars.

Since corona siderite mosaics are almost entirely restricted to primary intergranular and intragranular pores, at the expense of other mineral cements, they must be considered one of the earliest void fillers. They owe their quantitative importance in the Main, Two Foot and Raisdale Seams, to the high initial porosity. In some grain rich rocks about

PLATE 22 **Cements**

a) Subhedral siderite cement in optical continuity with siderite rinds. Main Seam, Skelton Beck.

b) Early diagenetic siderite crusts followed by poikilotopic calcite. Two Foot Seam, Ayton Mine.

c) Calcite pseudomorphs after acicular aragonite spars. Two Foot Seam, Rosedale.

d) Columnar aragonite spar pseudomorphed by calcite. Note large crystal, top centre, and small hexagonal crystal to the left are still aragonite.

x ~~200~~. 70

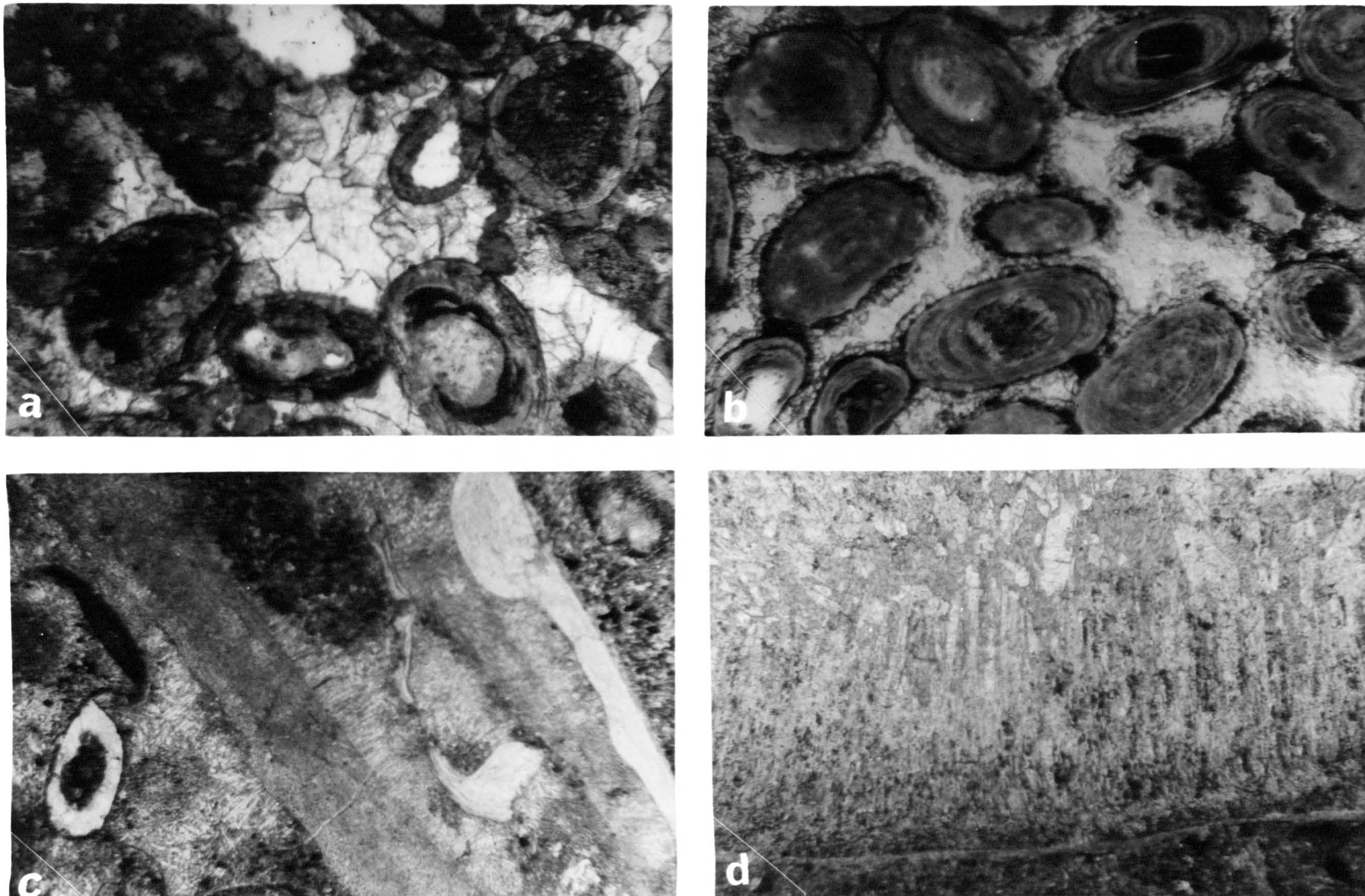


PLATE 22

40 percent initial porosity was available for the precipitation of mineral spar (page 153).

In the majority of cases the amount of siderite was just adequate to eliminate this porosity, but in some the crystals were too small to occlude the voids; siderite coronas were never completed to form mosaics and porosity remained for the deposition of later generations of spar. This occurs most frequently in the grainstone facies of the Two Foot and Raisdale Seams as a result of high primary porosities combined with narrow crystal coronas (plate 22b). By contrast in the Main Seam, where the porosities are lower (page 153), and the crystals larger, uncompleted mosaics (dog-tooth coronas) are only developed in particularly large pores; usually those produced by burrowing.

Crystal size and corona width remain remarkably constant within any given seam. In the Main Seam dog-tooth coronas are consistently between 100μ - 175μ in width and consist of up to three layers of crystals with maximum size about 150μ, while in the Two Foot a single layer of crystals 20μ- 50μ in width is characteristic, with occasional coronas reaching 200μ. As a general rule the larger the crystals the more bladed they become. Limited data from the Raisdale Seam suggest that the development of spar was much the same as in the Two Foot. Crystals from opposing pore walls usually impinge at a sharp divide, in these latter; a rare occurrence in the Main Seam.

The nature of the substrate appears to have little effect upon the growing crystals; crusts and overgrowths on ooliths, shells, intraclasts and matrix are similar both in size and shape.

Because the amount of primary porosity was small in the <u>Pecten</u>, <u>Avicula</u> and Osmotherley Seams (mainly wackestones and mudstones), siderite does not occur as a common void filler.

b) <u>Paragenesis</u> (~~Table~~ Fig. 38)

Judging from its petrographic uniformity only one generation of void filling siderite spar occurs in each ironstone seam and this always occupies the same position in the diagenetic sequence (page 256). Precipitation took place relatively early, but not before compaction and a certain amount of diagenetic alteration had taken place in the sediments (page 260); the majority of siderite replacement predates the deposition of the cements and void fillings but most other replacements occur after. In a limited number of cases aragonite shells underwent solution and collapsed or formed moulds before the precipitation of siderite, but once again the most important solution effects occurred after cementation (pages 167 - 171). Thus while most of the physical modifications to these rocks predate the spars, the major chemical alterations postdate them.

In many respects siderite spar resembles the earliest phases of calcite cementation observed in Pleistocene beach rocks (Friedman 1964, Matthews 1967). Although the causes are different the mechanism of formation was probably much the same. Friedman (1964, 1966) has shown that while aragonite spars may develop on the sea bed, calcite is not normally precipitated until lime sediments are withdrawn from contact with sea water by emergence. Similarly in these ironstones siderite cementation seems to have been retarded until the circulation of sea water was cut off, not by emergence, but by a layer of superincumbent sediment sufficient to cause the compactive effects described previously (pages 156 - 162).

Because the supply of siderite appears to have been limited, especially in the Two Foot and Raisdale Seams, it is more likely that it was derived within the seams than from without, through the expulsion of pore waters from the shales associated with them. While reducing conditions prevailed, iron leached from chamosite (pages 235 - 238) was probably accumulated as the bicarbonate by combination with carbon dioxide from the decomposition of organic matter in the sediment, and water. Once the pore waters were saturated, precipitation of siderite would be triggered off by the withdrawal of carbon dioxide.

5. <u>Aragonite</u>

Occasionally the place of siderite as princi~~ple~~pal early spar is taken by a second mineral, the precise nature of which is usually obscured by later replacement spars, such as ferroan and non ferroan calcite and sphalerite, but which there are strong reasons for suspecting was aragonite.

(i) The pseudomorph often preserves a distinctive columnar, acicular habit resembling that of aragonite (cf. Gevirtz and Friedman, 1966).

(ii) The mineral occurred principally in shelly ironstones with a strong preference for aragonitic shell substrates suggestive of syntaxial overgrowth.

(iii) Although ferroan calcite occurs abundantly as replacement spar, it is unknown for it to replace other sparry minerals with this one exception. This is suggestive of some special relationship between host and replacement spar (i.e. polymorphism).

In one occurrence it has been possible to verify this identification by the discovery of acicular aragonite relics corroded by ferroan and non ferroan calcite (plate 22d). The crystals show a hexagonal cross-section and negative biaxial interference figure of small 2V (18^o).

Where non-ferroan calcite (differentiated by staining) and sphalerite participate in the replacement the acicular habit is particularly well preserved. Ferroan calcite tends to be more destructive but the conspicuous habit may be preserved by dusty inclusions. Elsewhere the existence of primary aragonite is suspected even in the absence of this acicular habit, from the dusty appearance of some replacement spars, especially where there is evidence of a primary void having existed.

a) The Mosaics

Because of its habit aragonite formed distinctive voidal coronas. The original crystals were up to 600μ in length and often only 1 - 2μ

in diameter. It is clear that many coronas were a single crystal in width but others show more than one layer and an increase in crystal size towards the centre of the void. Uncompleted coronas, filled with later spars, occur quite commonly in shell cavities and umbrellas. Once again these mosaics are mainly restricted to primary voids from which they are designated as early spar. However, the mineral is also found in veinlets, possibly also of early date.

Unlike siderite, aragonite shows a distinct preference for certain types of substrata; overgrowths are much more common and better developed than crusts. Columnar coronas, with long straight compromise boundaries were usually inherited by syntaxial growth from primary aragonite shell structures (plate22d). In the event of the surface of the aragonite substrate being partially obscured, by matrix or possibly by organic debris, drusy growth was inhibited and interrupted coronas resulted. Crusts on less suitable substrates, calcite shells, ooliths, intraclasts and matrix were less well developed and generally took up a radiate habit rather than the columnar form (plate 22 c).

Although aragonite spar may have accounted for 20-30 percent of some rocks, its distribution even before replacement was very localised. Characteristically it occurred in shelly ironstones and hence while its pseudomorphs have been observed from the Main and Avicula Seams, it was most common in the shelly grainstone-packstone facies of the Two Foot and Raisdale Seams. Even here the development was patchy, giving rise to aragonitic concretions, which were accentuated during compaction ~~(fig. ——)~~. Superficially these concretions may resemble pebbles or be taken for ferroan calcite nodules, but petrographic work shows the sediment to be <u>in situ</u> ~~(fig. ——)~~ and the calcite to be a late stage replacement. The primary textures and deformation fabrics indicate the existence of a primary porosity, later infilled by aragonite coronas, now more or less obliterated.

b) <u>Paragenesis</u> (~~Table~~ Fig. 38).

Siderite and aragonite, the two early spars in the ironstones, have never been observed in direct association, but while siderite was precipitated after the main phase of compaction, aragonite was formed before or in part during deformation, and enabled normally spastolithic horizons to resist collapse. However, although the mineral was probably formed soon after deposition it seems unlikely, in an ironstone environment, that it should have been precipitated directly from sea water in the manner of recent interstitial aragonite in the Red Sea (Gevirtz and Friedman 1966). Rather its occurrence in shelly ironstones suggests that these seams provided sites for the solution as well as for the precipitation of the mineral. The petrographic evidence favours several phases of aragonite shell solution, some before cementation, some after (page 171) so that it may well be that while aragonite was being removed from some horizons it was being precipitated at others. Gevirtz and Friedman (1966, p. 148) draw attention to alternating periods of aragonite precipitation and removal in Red Sea lime muds, but point out that the terminal environment is one of aragonite solution. However, it is clear that under certain circumstances aragonite spars escape solution, although they normally undergo calcite replacement at a later stage (Cotter 1966). According to Gevirtz and Friedman (loc. sit.) and others the precipitation of aragonite is favoured by high temperatures (at least 30°C) and high salinities (recorded values of 292‰ and 270‰).

The Cleveland ironstones were probably deposited in warm waters; O_{16}/O_{18} ratios determined from belemnites from the overlying Grey Shales indicate average temperatures of around 20°C (Smethurst et al. 1965), but this would seem too low to maintain aragonite even if it were deposited. It must be concluded therefore that the temperature and possibly also the salinity of the pore waters was increased following deposition. This may suggest that evaporation took place incident upon local emergence of the oolite shoals. If evaporation did occur, capillary movement of the pore water may have been responsible for the transport of calcium carbonate to the sediment surface where precipitation was being induced. However, it must be pointed out that aragonite is highly soluble in fresh water, so that an arid or semi-arid climate is required, and small islands insufficient to support fresh water lenses (Stoddart and Cann 1965).

6. Calcite

Calcite is the most important of the late void fillers. It occurs as large crystals, up to about 10 mm. in major diameter, dark chocolate brown in hand specimen, and pale brown to colourless in thin section. The brown colour is rather unusual and first attracted the attention of Dunham (in Whitehead et al. 1951, p. 39). His measurements on a specimen from the Pecten Seam yielded a refractive index of ω=1.664 and indicated the presence of ankeritic calcite. The distribution of iron in the mineral is brought out very clearly by staining with potassium ferricyanide and allows a distinction to be made between what are feferred to here as high iron calcites (brown crystals staining dark blue) and low iron calcites (colourless crystals staining light blue). Although colour and stain may be used to give an indication of the relative amount of iron present, the depth of stain also depends on the relative solubility of the mineral, which is affected by the presence of other ions in solid solution (Dickson, 1966, p.494). No analyses for iron have been made so that the exact percentage is unknown; Dunham's measurements suggest a value of 3.5 percent $FeCO_3$ for the high iron calcite, provided that $MgCO_3$ and $MnCO_3$ are absent.

a) The Mosaics

Void filling calcite occurs almost exclusively as random spars, entirely without corona structure; that is to say the crystal seeding is haphazard by comparison with the early spars. In combination with the large crystal size, which frequently exceeds that of the individual voids, this makes the nature of the mosaics difficult to determine. Furthermore many crystals show more or less pronounced spectral extinction, have curved cleavages and curved intragranular boundaries, when developed. This phenomenon is most pronounced in the high iron calcites with average variations of around 30° per millimetre, but also occurs in some low iron crystals up to a maximum of about 5° per millimetre. Further work is necessary to show whether or not it is the presence of iron within the calcite which is responsible for this kind of straining. Spectral extinction may be accommodated by a number of subgrains within the main grain, but this is not necessarily the case; many void fillings are free of any division.

In the absence of well defined mosaics, and because of straining it becomes impossible to separate void filling spars from replacement spars on the basis of grain morphology (Folk 1965, p. 44). Only where there is independent evidence for a void, for example where calcite is found within uncompleted siderite coronas, or where solution-collapse has taken place (page 167), can directly precipitated calcite be identified with certainty. However, since many replacement spars contain relict textures, clear crystals free from inclusions may often be taken as indicative of void filling.

In practice very little difficulty arises in differentiating calcite as a primary void filler, because it is always found within uncompleted siderite or aragonite coronas. Here, apart from the extent of original porosity, the importance of the mineral depends on the effectiveness of the early spars in cementing the rock. Thus while it is not uncommon to find calcite as an intergranular cement in the

Two Foot Seam, it is much less common in the Main Seam, where only large primary intragranular pores and open burrows provide sufficient space as a rule, and rare in the Raisdale and other seams. Even in the Two Foot Seam where porosities rise to about 40 percent calcite rarely occupies more than 16 percent of this total. Both high iron and low iron calcites are present as cements in this seam, but with high iron calcite dominant.

It is when dealing with suspected secondary voids that the greatest difficulty arises in distinguishing drusy and replacement spars. Solution collapse occurs in ooliths, intraclasts and most importantly in shells. Once again both high and low iron calcites are present, with low iron crystals dominant in the Main and Two Foot Seams. Many of these cavities, even fairly large examples up to about 1 cm. in length, are infilled by a single crystal plate sometimes with pronounced poly-synthetic twinning; similarly groups of adjacent shell cavities. Calcite filled secondary voids occur in the majority of seams but are most important in the grain rich facies of the Main and Two Foot Seams, following the solution of aragonite shells. As pointed out by Bathurst (1964, p. 375) solution-deposition is favoured in rocks with initially high permeability, probably due to greater accessability to moving pore solutions.

Random calcite spars also occur in late stage cross-cutting veins, always filled with high iron crystals showing strong spectral extinction.

b) Paragenesis (~~Table~~ Fig. 38).

Although calcite postdates aragonite and siderite, its relationship to the other late spars varies; that is to say the petrographic evidence favours several generations of calcite spar, often with void filling and replacement taking place simultaneously (pages 248-250). For example in the Two Foot Seam at least three phases are present.

(i) During the first phase cementation was virtually completed by the precipitation of high iron calcite. However, seeding was highly irregular and small pockets of porosity remained for the precipitation of the next phase of spar. No replacement occurred at this stage.

(ii) Low iron calcite, with the exceptions noted above is restricted to secondary shrinkage and solution voids and therefore is judged to postdate phase (i). In addition the precipitation of sphalerite appears to intervene between the two. Locally replacement occurred at this time (pages 255).

(iii) Most calcite replacement and a certain amount of secondary void filling took place subsequent to phase (ii) and involves high iron calcite (see pages 255). The development of high iron calcite veins appears to be associated with this final phase.

How far this scheme may be extended to other seams is difficult to say. In the Main Seam low iron calcite void fillings (phase ii) precede high iron replacement spars (phase iii) but there is no evidence of phase (i). In consequence other late void fillers such as sphalerite and chalcedony appear to precede the deposition of calcite. Void filling calcite is much less common in the remaining seams where high iron replacement spars predominate (phase iii). (See ~~table~~ fig 38).

Whether the similarities between the phase (ii) spars from the Main and Two Foot Seams indicate parallel evolution or whether they were formed simultaneously is difficult to decide. Certainly the all pervading nature of the late phase (iii) replacement spars favours the supposition that they formed simultaneously as a result of a general mobilisation of pore water throughout the formation (pages 261-262)

Work by Oldershaw and Scoffin (1967) on the distribution of ferroan and non-ferroan calcite cements in the Halkin and Wenlock Limestones suggests that the iron in ferroan calcite may be derived from clay minerals. They find a distinct separation between first stage non-ferroan calcite cements, probably derived from the solution of aragonite shells, and second stage ferroan calcite, similar to the separation between siderite spars and calcite spars in the present deposits. The origin of the iron for incorporation in the calcite provides no problem. It may have been derived from the ironstones themselves or from the associated shales. In either case an abundant supply was available.

7. Sphalerite

Sphalerite is found in the Main, Two Foot, Raisdale and Avicula Seams, both as a void filler and replacement spar. The void fillings usually occur in secondary pores, but have also been observed in

PLATE 23 Void fillings

a) Open burrow infilled with (i) Siderite spar; (ii) Calcite spar; (iii) Chalcediform quartz. Main Seam, North Skelton.

x 30 (Crossed polars).

b) Shell cavities infilled with sphalerite. Main Seam, Normanby. x ~~200~~.70

c) Sphalerite void filling and replacement. Two Foot Seam, Raisdale. x ~~200~~.70

d) Shell void infilled with (i) aragonite; (ii) Sphalerite (top right). Aragonite is replaced by calcite (middle right) and sphalerite (middle left). x ~~200~~ 70

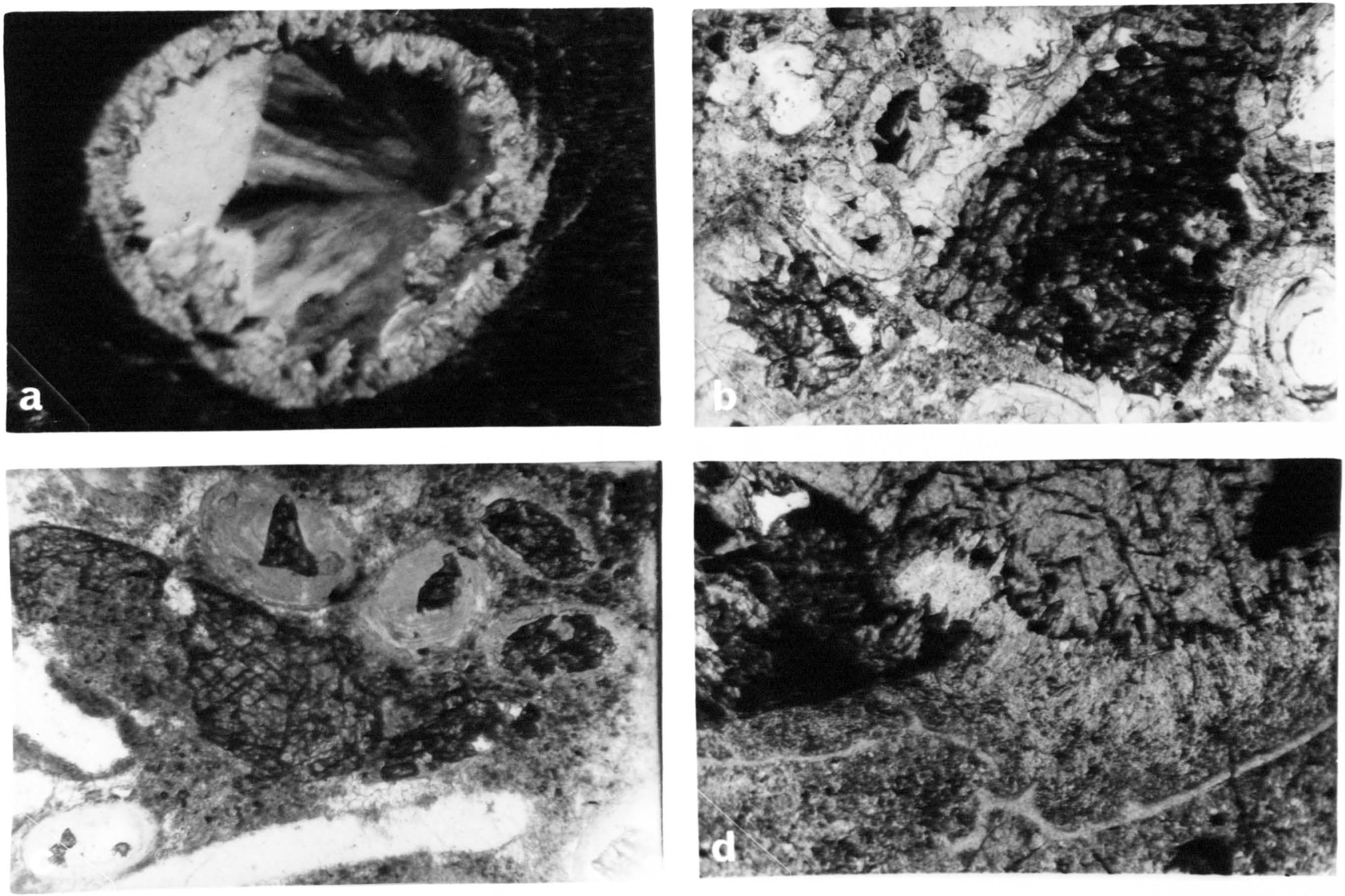


PLATE 23

primary intragranular voids in the Raisdale Seam (plate 23d).
In most cases there is no evidence of a mosaic, the cavities being filled by a single mineral plate. Crystal size is therefore dependent upon the size of each cavity. The maximum observed size was 2 mm.

Once again sphalerite is a late spar. It follows siderite and aragonite, and in the Two Foot Seam, the phase (i) calcite spar, but is euhedral to the later phases. It is also euhedral to quartz in the Main Seam ~~(Table)~~. The most likely source of the mineral is probably the shales of the Ironstone Formation. Here sphalerite occurs quite commonly in the cracks of septarian concretions in association with other late spars, calcite, barytes, kaolinite and also pyrite.

8. Quartz and Chalcedony

Quartz and chalcedony spars occur only in the Main Seam, where they are found as secondary void fillings, (in ooliths, intraclasts and shells) as well as replacement spars. Such fillings are common, although they rarely constitute more than a few percent of the total rock. Little difficulty arises in separating replacement spars, which are always filled with inclusions, from void fillers, often associated with collapse structures, although the mineral habit is precisely the same in both cases.

The distinction between chalcedony and quartz is similar to that between spectral and non-spectral calcite, with every variation between single unstrained crystals, strained but undivided crystals and grains consisting of a radiate mass of subgrains (plate 23a). The main crystals are usually equant with maximum diameters up to about 0.8 mm. (average about 0.5 mm.), while the subgrains are distinctly fibrous. Crystal seeding is haphazard and the mosaics therefore completely random.

Quartz and chalcedony clearly qualify as late spars; they postdate the deposition of siderite and are unknown in primary voids. However, quartz is euhedral to calcite where the two minerals occur in association (~~table~~ fig. 38).

Several modes of origin are possible for the mineral. In the first place it may have been derived within the seam following the solution of chamosite, and in the second from the shales associated with the seam as a result of pressure solution among the detrital quartz grains. The last appears the more feasible origin.

9. Other Minerals

Both barytes and kaolinite occur in the ironstone seams. Barytes occurs in small quantities in secondary voids in the Main Seam and care isneeded in order to differentiate it from quartz. It forms single crystal plates in the manner of sphalerite.

Kalinite is much more common in all the seams, but while in some instances it occurs as a void filler; for example in small septarian cracks, in most it is probably replacive (see pages 239 - 241). There is no distinction in mineral habit between these two, so that in individual cases it is difficult to differentiate.

10. Conclusions

The division between early and late spars is a striking one in the Cleveland Ironstone Seams (see ~~table~~ fig 38). While the early spars are characterised by small and delicate crystals in distinctive corona fabrics, the late spars are more coarsely crystalline and totally random. Straining occurs in both categories but is particularly conspicuous in the late spars, calcite and quartz. Differences in crystal size and seeding are probably dependent upon the concentration of the pore waters and upon the growing time, so that the differences in habit may reflect the gradual diminution of porosity in the sediments through diagenesis. During early diagenesis porosity is high, the pore waters mobile and precipitation appears to take place rapidly at many sites on the constituent grains, while during late diagenesis, when the movement of mineral ions is restricted, precipitation is slow and seeding localised.

VI DIAGENESIS (PART 2)

A. CHAMOSITE REPLACEMENT AND RECRYSTALLISATION

Chamosite is mainly an original halmyrolytic mineral, formed by the interaction of silicon aluminium and iron on the sea floor, but in places there is evidence of chamosite replacement and recrystallisation having taken place in these ironstones as in other deposits (see for example Déverin 1945, 1948).

The best evidence for chamosite replacement occurs in the presence of chamositised shell fragments, either loose in the sediment or as the nuclei of ooliths, especially in the Two Foot Seam (plate 6a). However, many of the cryptocrystalline chamosite mud grains which occur as nuclei were probably faecal pellets, which must have undergone rechamositisation even if they consisted simply of regurgitated chamosite mud, since they lack all sign of the cloudiness usual in faecel pellets (page 130). In all probability these replacements took place on the sea floor but it is possible that replacement may have continued even after burial.

The chamosite flakes which occur as oolith nuclei must have been formed by the porphyrotopic recrystallisation of chamosite. Unlike the flakes described by Pattinson (1964) which appear to have recrystallised within the ooliths, however, the present examples were clearly derived from outside the ooliths (page 107) presumably by the recrystallisation of chamosite mud; they appear too delicate to have been developed directly on the sea floor. Although chamosite mud was observed recrystallisating into radiating sub-spherulitic bundles in the Avicula Seam (plate 29a) these in no way resemble chamosite flakes and the precise origin of these interesting grains therefore remains a mystery in the Cleveland Ironstones.

B. PHOSPHATISATION

Chemical analyses of the Cleveland Ironstone Seams invariably indicate the presence of a small percentage of calcium phosphate running between 2-3% in the case of the workable parts of the Main Seam (see Hallimond 1925, p. 51). The greater part is attributable to the cryptocrystalline mineraloid collophane which may sometimes be recognised as a replacement mineral by its pale brown colour and isotropism. However, because it is difficult to detect in small amounts, Mann's (1950) spot test for phosphorus has been utilised in order to check the distribution of the mineral.

In this way it has been possible to show that collophane is not only present in the intraclasts (page 129) but also in the other allochems and in the matrix. Reasons have been advanced for regarding the phosphatisation as a sea floor reaction (page 129) but it is clear that replacement continued even after the burial of the sediments. Phosphatised ooliths and shells, from the Main, Two Foot and Raisdale Seams, occur in small groups rather than scattered indiscriminately through the sediment as would be the case had they been replaced in the manner of the intraclasts. In one particularly interesting

PLATE 24.

a) Siderite rinds on ooliths fromMain Seam, North Skelton. x ~~200~~. 70

b) Irregular siderite replacement in ooliths. Main Seam, Skelton Beck. x ~~200~~. 70

c) Siderite rind replacing chamosite.oolith. Electron micrograph (top right, siderite cement; centre, siderite rind; bottom right, chamosite oolith. x 8,000

d) Replacement of ooliths by opal. Main Seam, North Skelton. (Note septariate cracking) x ~~200~~. 70

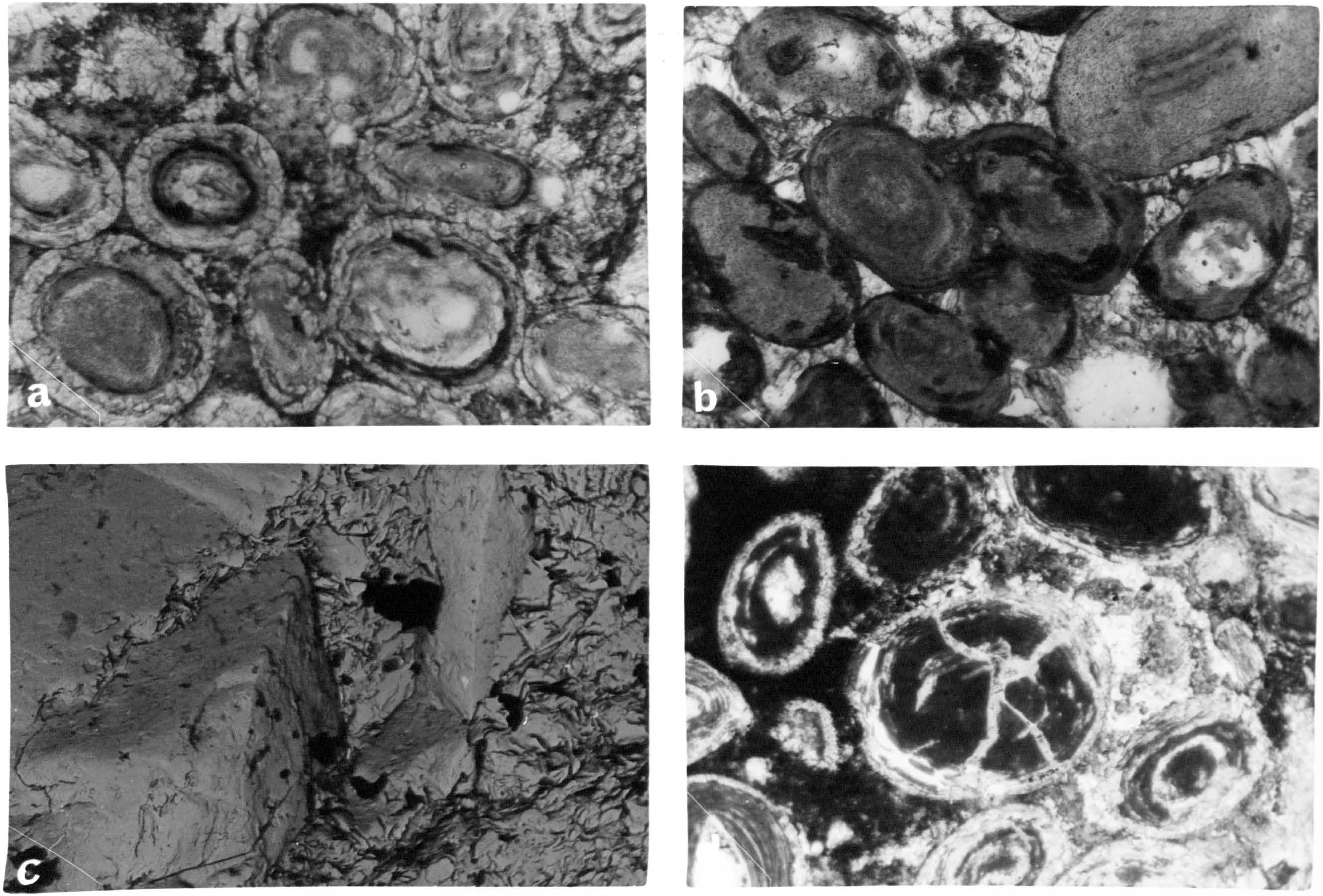


PLATE 24

occurrence, in the Two Foot Seam at Staithes colloform phosphate patches up to 5 mm. across are found invading the matrix of a shelly packstone (plate 29b). Under crossed nichols the collophane is seen to be crowded with small siderite grains indicating that sideritisation was already in progress when phosphate was introduced. The fact that collophane undergoes replacement by calcite in the same rock also indicates that it is of early diagenetic origin, and it is probable that phosphatisation was partly contemporaneous with the formation of the siderite microsparites.

The origin of the phosphate provides no problems. Staining consistantly reveals small percentages of phosphate in the matrix of the ironstones especially in the vicinity of burrow and faecel material, which could have been mobilised and reprecipitated during early diagenesis.

Hallimond (1925, p. 52) considered the occurrence of 7.14 percent $Ca_3(PO_4)_2$ in the 'dogger stone' from the Cleveland Main Seam (probably the Middle Dogger Band) exceptional but staining suggests that there is always considerably more collophane in the siderite wackestone-mudstone facies than in the grainstone-packstone facies, probably because of the higher percentage of faecal material (page 132).

C. PYRITISATION

Pyrite, possibly accompanied by other iron sulphides, is not an uncommon constituent in the ironstone seams. It occurs both in matrix and grains usually in finely disseminated form, but occasionally as small pyritospheres (60μ in diameter on average) in the former, or as complete pseudomorphs in the latter. However the amount rarely rises above 1-2% with some notable exceptions.

1. The 'Sulphur Band'

This thin bed of pyritic oolite, which occurs at the top of the Main Seam (page 74) is one of the most remarkable horizons in the Cleveland Ore field. In places it probably consists of 50-60 percent pyrite and is the only rock which may be justifiably assigned to the sulphide facies of James' (1951) scheme. However, from the petrographic evidence there can be no doubt that this is not a primary ore type; the pyrite is entirely secondary in origin and is mainly developed at the expense of chamosite (see Hallimond 1925, p. 53 and Dunham in Whitehead et al. 1952, p. 47).

As pointed out by Hallimond (loc. cit.) the bed varies slightly from locality to locality, sometimes passing gradationally down into the Main Seam (e.g. Upleatham Mine) and sometimes separated from it by a thin siderite mudstone and a sharp disconformity (Ayton, Roseberry, N. Skelton, Lumpsey, Kilton Mines). On stratigraphic grounds this disconformity is believed to mark the junction between the Upper and

Middle Lias, the 'Sulphur Band' in fact being the basal bed of the Upper Lias (page 174). Although the 'Sulphur Band' and its equivalents have been identified throughout the area covered by this study, pyritous oolites are only developed where the Upper Lias rests directly on the Main Seam; to the south and east of the workable orefield, where the *hawskerense* shales intervene, the equivalent of the 'Sulphur Band' is a black finely laminated pyritic shale (see page 174 and fig. 23).

a) The Black Shale comprises graded laminations of fine and very fine grained sand passing upwards into silt and then into bituminous shale. The thickness of the individual laminae, which partake the appearance of varves, varies between 1-3 mm., so that there must be between 70 to 100 varves in the total 6 inches of shale. Pyrite was probably originally deposited through the activity of sulphate reducing bacteria in the bituminous shale parts of the laminae, but during diagenesis the mineral appears to have migrated downwards into the sand fraction and is concentrated in particular at the sharp shale-sand junctions between the varves. At Botton Head and Raisdale ripple marked lenses of pyritic oolite occur interlaminated with the Black Shale and in this case it seems clear that sulphide has migrated from the shale into the oolite lenses.

b) The laminated siderite mudstone which occurs interbedded with the pyritic oolite of the 'Sulphur Band' in the southerly group of mines

PLATE 25.

a) Former aragonite shell showing euhedral siderite replacement spar and later cavity filling with siderite and calcite (Note siderite same age as cement) x ~~200~~. 70

b) Sideritised shell fragment. Main Seam, Upleatham. x ~~200~~. 70

c) Almost totally sideritised chamosite oolite. Two Foot Seam, Rosedale x~~60~~. 20

d) Terriginous mudstone replaced by acicular aragonite. now pseudomorphed by calcite (Note aragonite shell substrate bottom right) x ~~60~~. 20

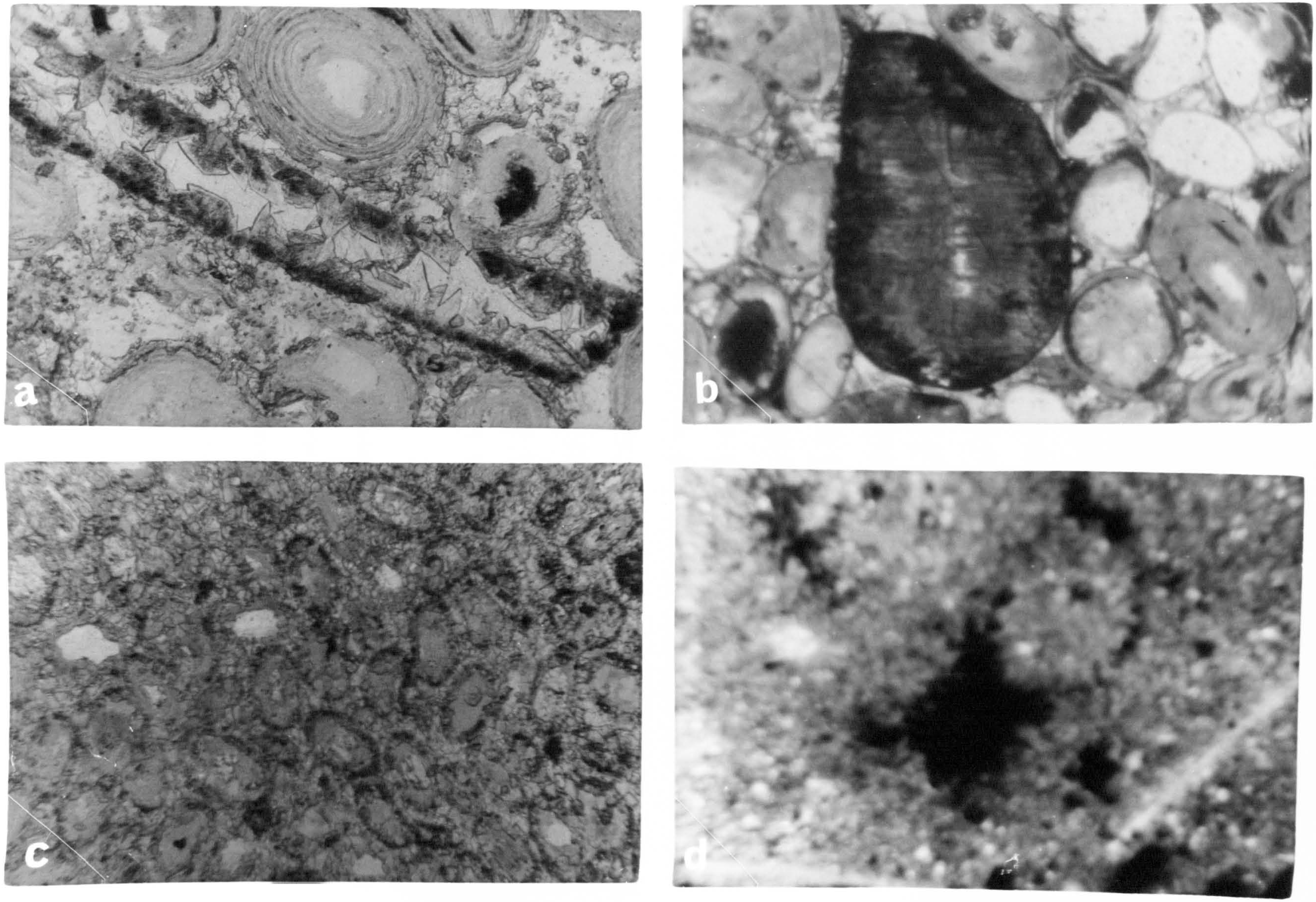


PLATE 25

investigated during this study appears to be equivalent to the Black Shale (see page 174); it contains the same Arenicolites burrows and shows a pronounced lamination in hand specimen (see plate 26). However in thin section the mudstone is found to consist of even grained coarse siderite microsparite without any sign of the lamination. Furthermore although disseminated pyrite occurs the percentage is far lower than in the Black Shale. There is no evidence to suggest that the pyrite is replaced by siderite and indeed this is most unlikely on theoretical grounds since siderite will not form in the presence of free sulphur ions (page 319). The siderite must therefore have been introduced following the migration of the pyrite from the shales.

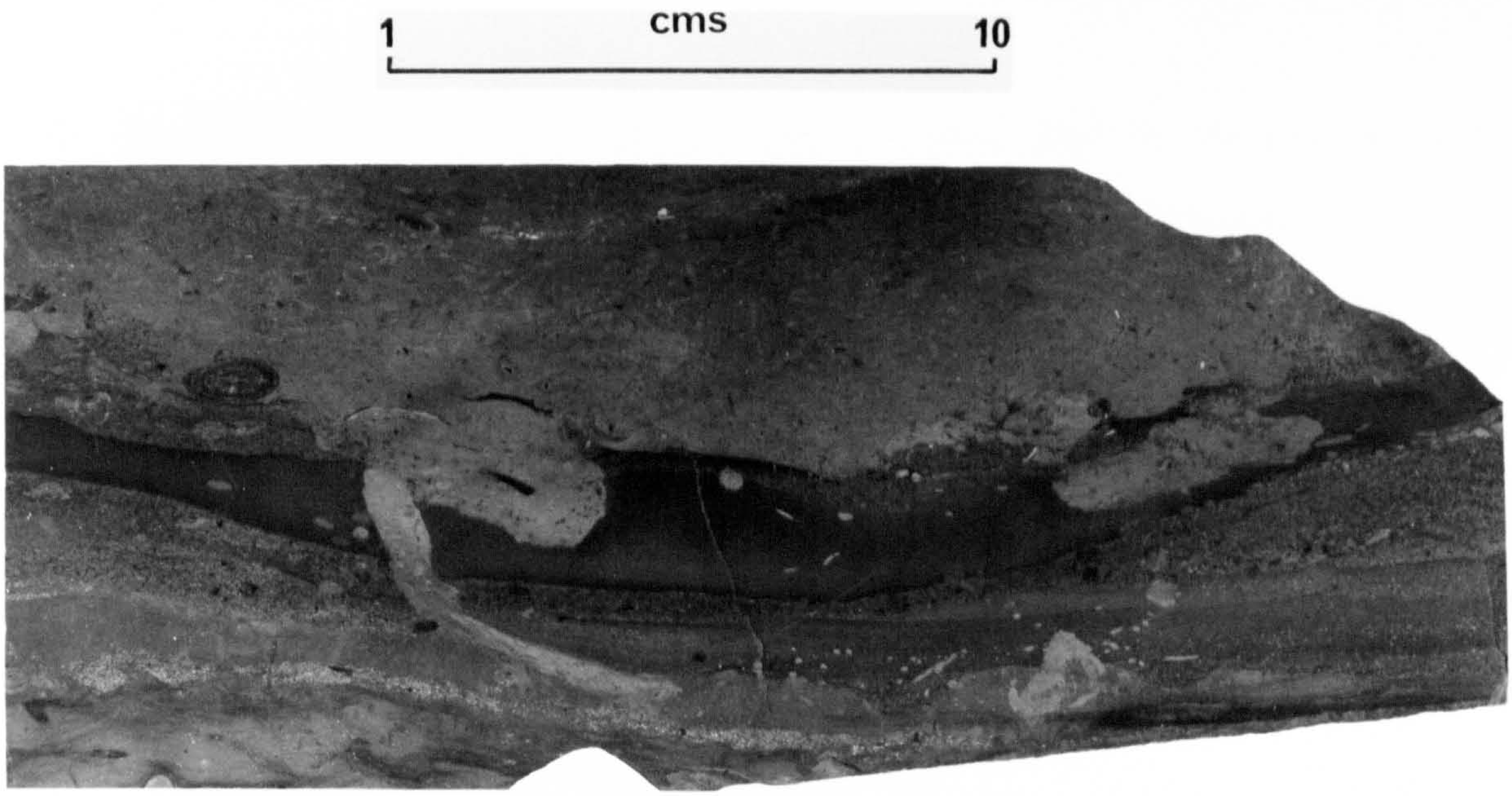
However, in some cases pyrite appears to have been re-introduced into the mudstone layers as a finely disseminated replacement of the siderite, giving a golden sheen in hand specimens. This presumably indicates a second period of pyrite migration following the formation of the siderite microsparites.

c) The pyritic oolite which is found interlaminated with the siderite mudstone (plate 28a) and which preserves most beautiful ripple marks appears to have attracted the majority of pyrite liberated from the Black Shale. In thin section (plate 27a) it is found to be a spastolithic grainstone dominantly composed of ooliths but with occasional shells and intraclasts, all replaced to a greater or lesser degree by pyrite. Various stages in the replacement process are evident.

Unreplaced ooliths, giving only weak X-ray powder photographs consist of weakly birefringent chamosite heavily stained with red brown limonite. These occur in rare isolated lenses, which escaped heavy pyritisation for some unknown reason, and are also scattered randomly through the more intensely replaced oolites. The sulphide clearly picks out weak points in the oolitic structure, working along interlamina sutures and therefore appearing concordant with the oolitic envelope at first glance. However, in detail the pyrite is found to cross from lamina to lamina, to work along the cleavage planes of chamosite flakes where they occur as nuclei, and to run in tiny veinlets through the oolitic envelope. As the percentage of pyrite increases the red brown colouration disappears leaving colourless isotropic chamosite, which is gradually eliminated as replacement nears completion. Although some ooliths are totally converted to pyrite and lack all trace of internal structure, the majority retain a relict oolitic structure due to the presence of cryptocrystalline chamosite (plate 27 b).

On the other hand intraclasts which lack internal structure, show a much more random type of replacement, with small patches of pyrite which eventually join to form an anastomosing mass of sulphide with 'floating' relics of the original grain. Of the shell fragments calcite genera are usually unaffected but aragonitic shells undergo replacement in the same manner as the ooliths, with pyrite working along the original lamella structures.

PLATE 26. Sulphur band with ripple marked pyritic oolite and sideritised laminated shale. North Skelton.


1
cms
10

a

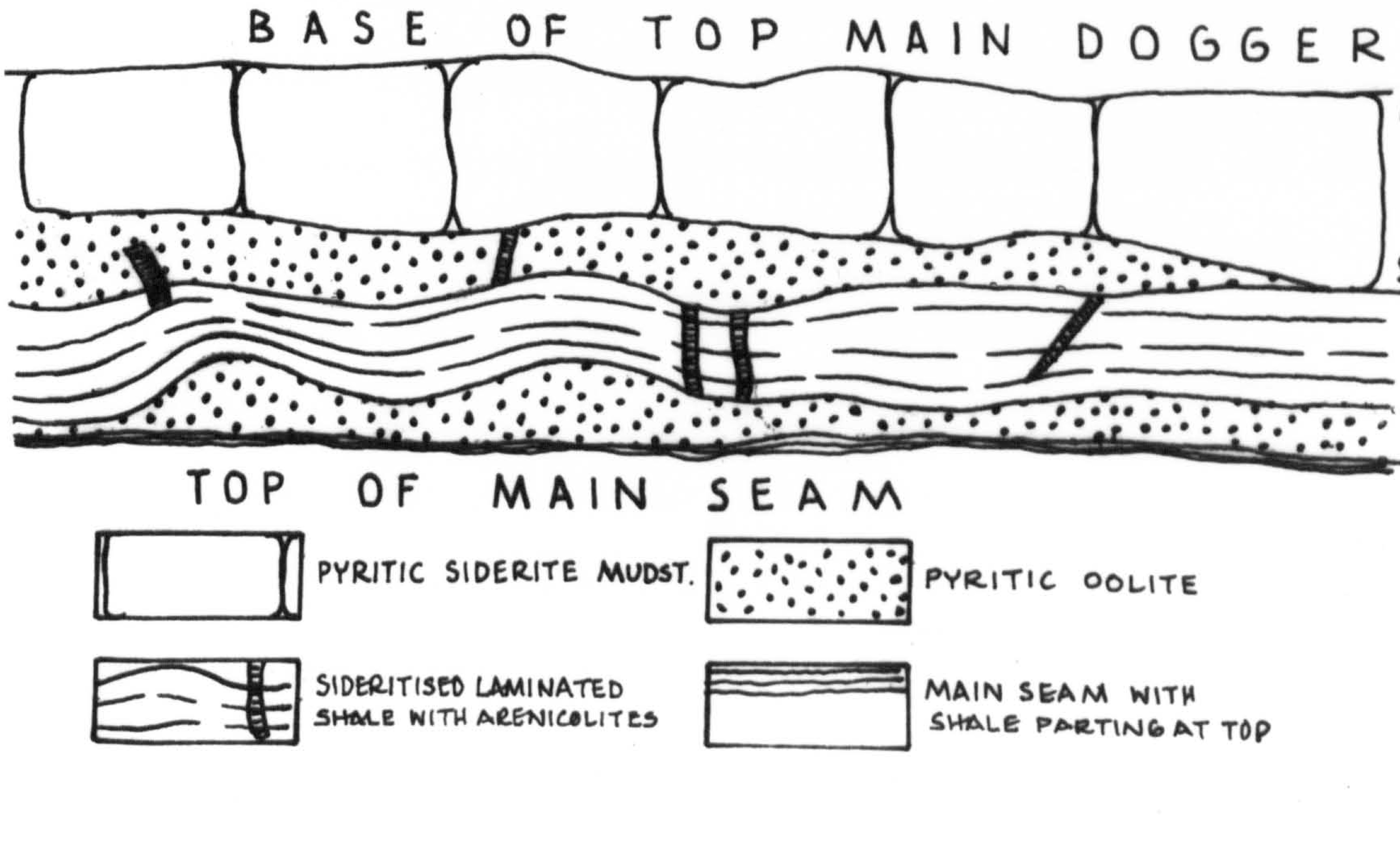

BASE OF TOP MAIN DOGGER
9"
TOP OF MAIN SEAM
PYRITIC SIDERITE MUDST.
PYRITIC OOLITE
SIDERITISED LAMINATED SHALE WITH ARENICOLITES
MAIN SEAM WITH SHALE PARTING AT TOP

PLATE 26

d) <u>The Sulphur Band at Upleatham Mine</u> as described by Hallimond (loc. cit.) appears to differ from that in the more southerly mines; not only is there no definite boundary between the pyritised oolite and the Main Seam, but the pyritised grains occur in an unaltered matrix of chamosite mud (Hallimond 1925, p. 122, fig. 2). Apparently pyritised intraclasts make their appearance within the top foot of the seam, and are joined at higher levels by pyritous oololiths which increase in importance towards the 'Sulphur Band' proper.

e) <u>Conclusions</u>

There can be little doubt that the pyritisation of the 'Sulphur Band' took place as a direct result of the superimposition of a black bituminous and pyritic shale upon the Main Seam at the time of the Upper Lias transgression. However, the sequence of events is somewhat complex and there are several puzzling anomalies. What, for example, is the significance of the variation between Upleatham Mine and the southerly group of mines? Why does limonite occur in some instances and at what stage was it introduced; prior to or after pyritisation? Hallimond (1925, p. 54) among other conclusions determined:-

(i) that pyritisation "took place in the sea floor material while it was still undergoing redistribution and consolidation to form the present rock."

(ii) that "the conditions were temporary, and were approximately, but not quite contemporaneous over the area."

Broadly the present writer agrees with these conclusions but finds the situation considerably complicated by the time interval which exists between the 'Sulphur Band' which belongs to the Upper Lias and the Main Seam which belongs to the apyrenum subzone of the Middle Lias, an interval probably in excess of half a million years. The writer draws the following tentative conclusions:

(i) The oolitic material for the 'Sulphur Band' was probably provided by the reworking of ooliths from the top of the Main Seam during the earliest phases of the Upper Lias transgression.

(ii) These ooliths were redistributed, winnowed into ripples and possibly oxidised to a certain extent, and then buried by a thin deposit of varved bituminous shale in which pyrite was developing syngenetically.

(iii) With the onset of compaction the ooliths were spastolithised and pyrite was mobilised and migrated into the oolite lenses trapped within the shale and to a lesser extent into the upper part of the Main Seam.

(iv) Following the migration of pyrite the black shale was replaced by siderite probably derived from the overlying Top Main Dogger, whichmay well have been undergoing sideritisation at the same time.

(v) At a later stage pyrite was remobilised and re-introduced into some of the siderite mudstones of the 'Sulphur Band' as a replacement.

PLATE 27 Sulphur Band

a) Pyritic ooliths interlaminated with siderite mudstone (after bituminous shale) and quartz silt (light colour) x 14.

b) Pyritised spastolithic grainstone x 20.

a) and b). North Skelton.

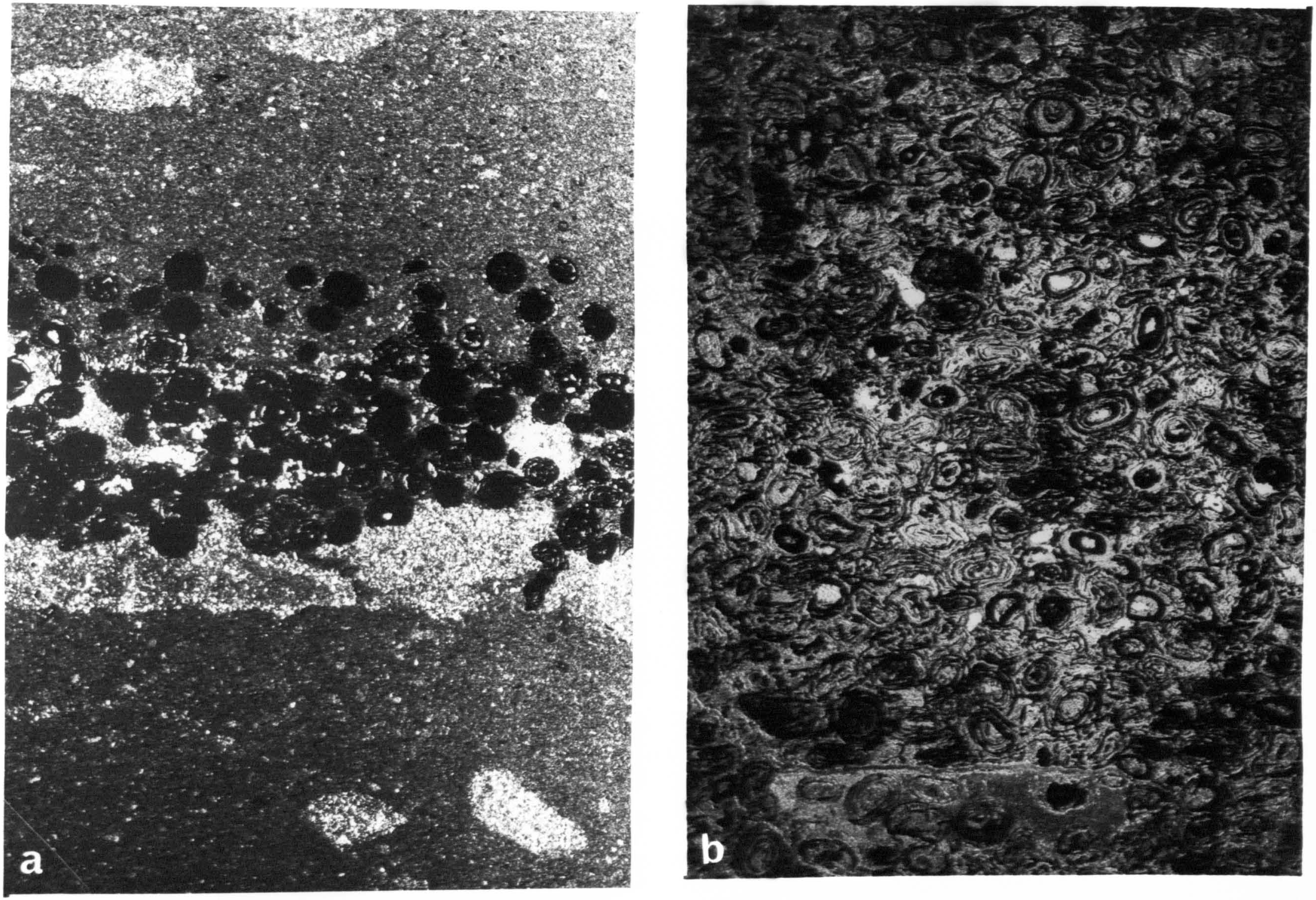


PLATE 27

2. The Avicula Seam

Concentrations of pyrite occur at the top of both blocks of the *Avicula* Seam in the 'Scrap Band' and the 'Bearing Stone' (pages 29). Both these horizons comprise beds of spastolithic green oolite with occasional aragonite concretions. The pyrite occurs finely disseminated through the matrix and within the calcite replacement spars developed after the original aragonite, as well as in pseudomorphs after the ooliths. However replacement is much more localised than in the case of the 'Sulphur Band' tending to form pyrite concretions, which may be several inches across, and which sometimes develop good crystal faces.

Once again these beds are overlain by dark pyritic shales, in the case of the Top Block, the basal shales of the *gibbosus* subzone and in the case of the Bottom Block the Middle *Avicula* Shale, and in all probability the pyrite was mobilised from these shales during early diagenesis.

3. The Two Foot and Raisdale Seams

The spastolithic chamosite oolite layers with aragonite concretions from the Two Foot and Raisdale Seams are closely analogous to the spastolithic horizons of the *Avicula* Seam and these too contain patches of pyritised oolite where they are directly overlain or underlain by the *gibbosus* shales. Here pyritisation appears to have taken place prior to compaction for pyritous ooliths usually escape deformation.

4. Paragenesis

Pyrite appears to be a very mobile mineral during the early stages of diagenesis. It apparently forms syngenetically in the shales but during compaction readily migrates either towards burrows within the shales themselves (pages 22, 37) or towards the depositional interfaces of the ironstone seams, where it is precipitated at the expense of the pre-existing minerals. Probably because of their high porosity grainstone facies provide particularly suitable sites for replacement.

Replacement is mainly restricted to the primary constituents and is especially common in the chamosite ooliths but may also occur in some early diagenetic minerals such as the siderite microsparites and possibly in aragonite. It may either precede or accompany the process of spastolithisation, and never occurs as a replacement of the siderite cements. All the petrographic evidence points to the conclusion that pyrite is an early diagenetic spar therefore. Once in place late diagenetic modifications to the seams, such as the introduction of calcite, appear to have very little effect upon the mineral. Even after heavy calcite replacement pyrite remains completely free of replacement.

However, in the top few feet of the Main Seam gypsum may appear as a late diagenetic spar in replacement of ooliths and intraclasts possibly indicating some slight mobilisation of sulphate from the decomposition of pyrite at this late stage.

D. ARAGONITE REPLACEMENT

Because of the pervading influence of subsequent calcite replacement (pages 247-248) it is impossible to judge to what extent aragonite replacement may have accompanied aragonite cementation (pages 181-184). However, in one or two instances, in the matrix of former aragonite concretions from the Two Foot and Raisdale Seams, calcite pseudomorphs after acicular aragonite pseudospars appear to occur. The latter crystals reach an apparent maximum length of about 700 μ and seem to have grown as syntaxial overgrowths upon the aragonitic shell debris in the matrix (plate 25d). That the original spar was of replacement origin is proved by the presence of abundant silt and clay sized inclusions which are retained within the secondary calcite.

Direct evidence for the paragenesis of these spars is absent, although they obviously formed prior to the introduction of calcite. There is every likelihood, however, that they formed simultaneously with the aragonite cements.

E. SIDERITE MICROSPARS

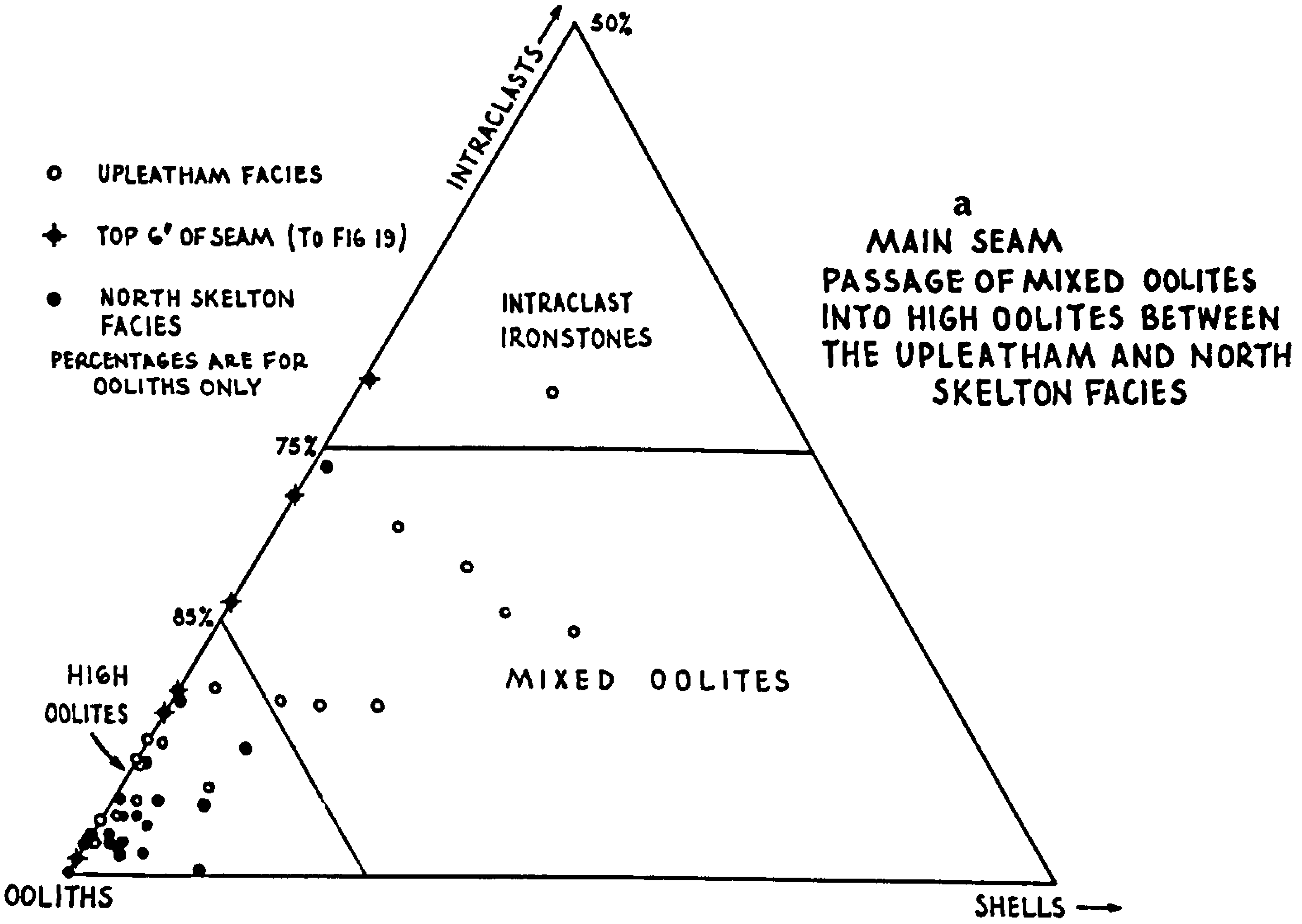
The question of whether siderite is an original or a secondary constituent in the matrices of the Cleveland Ironstone Seams has already been touched upon briefly on pages 146-147 . Doubt arises because while the distinction between chamositic and sideritic facies appears to be mainly original, the textures associated with siderite are undoubtedly diagenetic.

1. Grain Size

Siderite characteristically occurs in the matrix of the ironstones as small equant crystals, remarkably uniform in size in any one thin section, either scattered randomly in a matrix of clay mineral or forming xenotopic-granular mosaics (see Friedman 1965). At the lowest limit the grain size approaches the resolving power of the microscope but there is an apparent range in size between about 5-50μ. In the strictest sense therefore, siderite mudstone is a misnomer since the individual crystals lie within the silt range (4-64μ). Siderite siltstone is equally unsuitable, however, because there is no suggestion that the siderite is detrital. Quite the reverse, the general uniformity of size points to diagenetic growth. For this reason the terms microspar (4-31μ) and pseudospar (>31μ) introduced by Folk (1965) for precisely similar fabrics in limestones, have been adopted, when considering siderite from a diagenetic viewpoint, but the name siderite mudstone has been retained in general discussion, because it is valuable in the context of the Dunham limestone classification (pages 98-99).

2. The quantitative importance of siderite microspars and pseudospars

Without chemical analysis it is difficult to estimate the precise amount of siderite in the matrix of an ironstone, relative to chamosite and other clay minerals and quartz. Insoluble residues give a rough guide to purity but are unreliable because chamosite, and to a lesser extent other clay minerals, are removed by hot hydrochloric acid. Percentages have therefore been estimated in thin section. For this


50%
INTRACLASTS
UPLEATHAM FACIES
TOP 6' OF SEAM (TO FIG 19)
NORTH SKELTON FACIES
PERCENTAGES ARE FOR OOLITHS ONLY
INTRACLAST IRONSTONES
75%
85%
MIXED OOLITES
HIGH OOLITES
OOLITHS
SHELLS
a
MAIN SEAM
PASSAGE OF MIXED OOLITES INTO HIGH OOLITES BETWEEN THE UPLEATHAM AND NORTH SKELTON FACIES

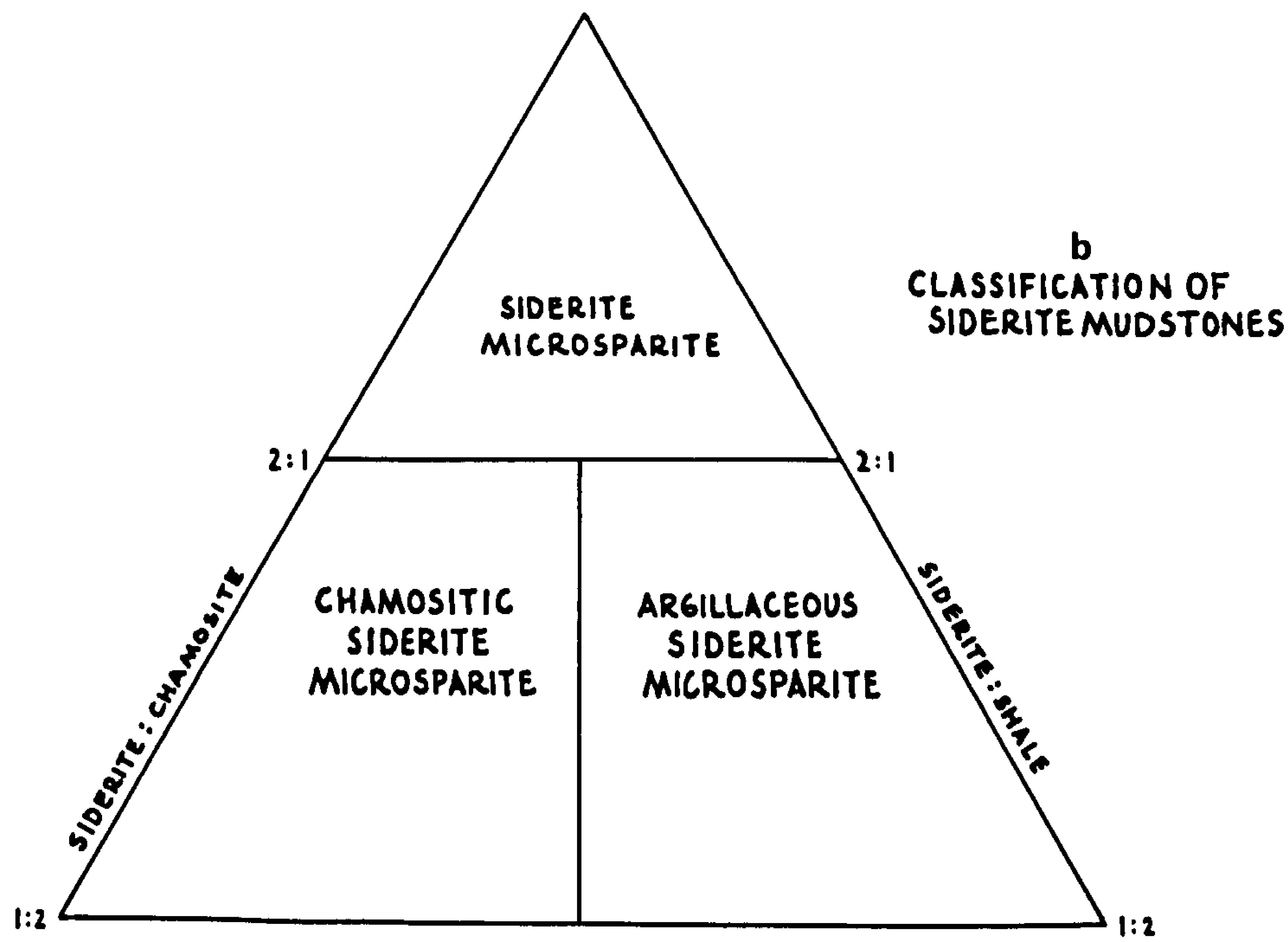

SIDERITE MICROSPARITE
2:1
2:1
CHAMOSITIC SIDERITE MICROSPARITE
ARGILLACEOUS SIDERITE MICROSPARITE
SIDERITE : CHAMOSITE
SIDERITE : SHALE
1:2
1:2
b
CLASSIFICATION OF SIDERITE MUDSTONES

FIG. 36.

purpose it is necessary to make counts near the edge of the slide in order to avoid grain overlap.

Even in the purest samples clay minerals are present both within and between the siderite grains, in amounts of up to about 10-20 percent of the rock. Nevertheless the grains are more or less interlocking. With increasing clay mineral content the siderite becomes more clouded by inclusions, and less and less interlocking until the siderite framework becomes first interrupted and then breaks down completely leaving the siderite grains 'floating' in the clay minerals. The spectrum of sideritic rocks is therefore broken down in the manner shown in figure 36 b.

On close examination the majority of siderite mudstone are seen to be either chamositic siderite microsparites or argillaceous siderite microsparites. In the Top Main Dogger, Main, Pecten and Avicula Seams complete transitions exist between chamositic and argillaceous siderite microsparites but in the remaining seams chamosite is subordinate to other clay minerals. In the Main Seam exploitation was carried into the chamosite-siderite mudstones but discontinued in the more argillaceous mudstones.

3. Textures

a) Fine grained siderite microsparites (4μ - 10μ)

Fine grained microsparites are typical of the Osmotherley, Avicula (5μ - 20μ) and Raisdale Seams (4μ - 10μ). The siderite grains are equant but anhedral and may be either floating or form a disrupted framework, but a large amount of clay mineral is always present both within and between the grains so that most of these rocks are classed as argillaceous siderite mudstones. Seeding is random but the grains usually occur in cloudy aggregates sieved with inclusions which give the rocks a blotchy appearance in thin section ~~(plate)~~. As a rule these aggregates form a disrupted framework with the clay minerals, but in the more sideritic examples the cloudy areas are separated by clear crystals of similar size. Just conceivably they may be the relics of some original texture such as might be produced by faecal pellets, but more probably this is a diagenetic effect, produced by segregation. In this case the cloudy crystals predate the clear, indicating that the siderite gained a greater facility for the expulsion of impurities with time. Very similar aggregates occur in sideritic calcite mudstone concretions.~~(page~~

In hand specimen this kind of mudstone is smooth textured, and buff in colour when fresh, but weathers rapidly. On the foreshore the typical weathering colour is scarlet or vermilion.

b) <u>Coarse grained microsparites</u> (10-31μ)

Coarse grained microspar crystals occur through the whole range of sideritic rocks from sideritic shales and chamosite mudstones through to siderite mudstones, in the Top Main Dogger (10μ–30μ), Main (10μ– 80μ) <u>Pecten</u> (10μ– 30μ) and Two Foot Seams (10μ– 30μ). Normally the crystal size does not exceed 30μ, although coarser areas of pseudospar occur in places in the Main Seam (see on), and the size remains approximately the same regardless of the percentage of siderite present. The more sideritic the rock, therefore, the greater the number of siderite crystals.

In the chamositic facies of the Main Seam and in the sideritic shales associated with all these ironstones siderite occurs as isolated equant anhedral or even euhedral crystals floating in clay mineral. The most characteristic feature of these crystals is the presence of more or less well defined cloudy cores, which like the enclosing crystals may be either anhedral or euhedral (plate 16b). Since the whole grains, core and perifery are optically continuous, it seems most unlikely that these cores should be dolomite as postulated by Hallimond (1925, p. 45). Like the cloudiness in the fine grained microspar aggregates these cores probably result because the expulsion of clay and organic material was less efficient during early siderite growth. A similar phenomenon occurs in dolomite pseudospars (Murray 1964) and is attributable to grain enlargement resulting from displacive replacement. The precise mechanism by which the impurities are removed from the growing crystals, however, is unknown. The presence of euhedral grystals may indicate the operation of solution-deposition on a micro-scale.

In the chamositic and argillaceous siderite microsparites, the microspar crystals gradually become sufficiently abundant to form a disrupted framework, but they do not show the same tendency to combine as aggregates as in the case of the fine grained microsparites. A large percentage of clay mineral is preserved between the individual crystals, and the cloudy cores remain ~~(plate)~~.

It is only in the siderite mudstones proper ($>^2/_3$ siderite) that the siderite frameworks become complete, and eventually interlocking (plate 36b). At the same time more impurities are expelled from the growing crystals and the cloudy cores disappear. Even so a certain amount of clay and silt remains trapped between the grains and a certain amount of clay is retained within the individual crystals.

On the whole the coarse grained microsparites tend to be more resistant to weathering than their fine grained counterparts. They are rough in texture and weather to crimson shades on the foreshore.

c) Siderite pseudosparites

Occasionally in the Main Seam siderite mosaics of the last type exceed 31μ in mean grain size and classify as pseudospars. These only occur in clear interlocking siderite mosaics, and are associated with the development of nodules and septarian cracking within the ironstone, indicative of a certain amount of diagenetic segregation. The cause of this further enlargement may therefore be somewhat different from that in the microspars where evidence of diagenetic segregation is absent.

d) Problematical microspars and pseudospars

Irregularities in the normal microspar frameworks, complete and disrupted, occur in the form of discrete very fine sand or fine sand aggregates of clear light brown or colourless siderite crystals (plate 15a,b). Some of these aggregates may contain cored crystals but not necessarily so. They are most common in the coarse grained microsparites of the Main, Pecten and Two Foot Seams (up to about 5% of the matrix in some cases) but also occur in the remaining seams to a lesser extent. They may arise in several ways:-

(i) Some may represent true pore fillings between faecal pellets (plate 12b), in which case the margins are concave inwards with angular projections into the matrix of the same form as spar filled cavities between ooliths for example. However, the more indefinite the pellets become the more difficult it is to separate this fabric from others resulting by replacement.

(ii) Most of these aggregates probably arise through the replacement of coarse grained elements in the original sediment; quartz and mica sand grains, small fragments of chamosite, shell debris, or plant tissue. Occasional relics of quartz, mica and chamosite remain within some aggregates. Others show by their external form that they are pseudomorphs after micaceous minerals or shells. However, many lack a distinctive form, and more than anything else it is the distribution of these bodies which suggests they may have been detrital quartz grains. They are particularly common in the middle part of the Main Seam immediately before it passes into silty shale, especially in the infillings of burrows. Exactly why quartz silt should be concentrated in the burrows is difficult to say but silt plugged burrows are a common feature in the shales. In some cases the silt may have been drifted into the burrows following their evacuation, but in many instances the burrowing organism itself appears to have been responsible for the expulsion of clay grade material and the concentration of silt, which occurs as a concentric lining to the burrow (plate 15b).

(iii) Some micas surrounded by clear siderite crusts do not appear to have suffered any replacement. Either the crusts occur in replacement of the matrix orerelative shrinkage has taken place between mica and matrix.

4. <u>The effects of burrowing and compaction</u>

The presence of a burrow in the matrix may be revealed in several ways depending upon the type of siderite mudstone.

a) <u>Chamositic and argillaceous siderite microsparites</u>

In this suite of sideritic rocks burrows are shown as follows:-

(i) By variations in the packing of the siderite framework, or in other words in the amount of clay mineral between the siderite grains. In some cases the packing is improved in the burrows, in others the reverse pertains.

(ii) From the tendency for the microspar crystals and aggregates to be concentrated in zones or aligned in trails both in and around the burrows. Longitudinal sections through these structured tubular burrows reveal a succession of 'U' shaped surfaces picked out by siderite, and seen in cross-section as crude cconcentric structures, marking the periodic progress of the burrowing organism through the sediment (plates 15a, b, c.).

b) Siderite microsparites (Sensu stricto)

In the siderite microsparites, where the siderite frameworks are completed, variations in grain packing are less important, and the structuring of the burrows is obscured. Burrows are shown by:-

(i) Variations in the clarity of the microspar caused by differences in the amount of clay mineral included within the grains. As with packing the relative cloudiness of burrow and host matrix varies.

(ii) Changes in grain size. For example the interburrowing of coarse microspar with pseudospar, which results in the development of septarian cracks as described previously (plate 36b).

c) The effects of compaction

During compaction burrows behave differently depending upon the relative proportions of siderite and clay mineral. Thus deformation is most severe in the chamositic and argillaceous siderite microsparites, the absolute distortion depending on the relative percentage of siderite in burrow and host matrix. It is least in the siderite microsparites, where the frameworks of siderite resisted compaction and preserved round tubular burrows undeformed.

The only type of sedimentary structure which can be observed in the siderite mudstones, other than the burrows, occurs in the chamositic and argillaceous siderite mudstones, and is the streakiness previously attributed to flowage resulting from the pressure of compaction (pages 155-156).

The question now arises as to how far these inhomogeneities may be used to infer the paragenesis of siderite. There are three main possibilities:-

(i) that siderite was present, either as detrital grains or as an early diagenetic mineral before the onset of burrowing.

(ii) that selective sideritisation took place after burrowing but before compaction as a result of mixing of iron-rich with iron-poor muds, or fine grained sediment with coarse, or because burrowing affected the distribution of Eh and pH in the deposits.

(iii) that selective sideritisation took place after burrowing.

Taken by themselves the textures from the chamositic and argillaceous siderite microsparites cannot be said to be diagnostic one way or the other. For example, although the streakiness produced by burrowing and compaction is clearly a primary texture it is not possible to say whether siderite was directly involved or developed selectively during subsequent diagenesis. In the case of the microspar aggregates formed in replacement of quartz (page 211) the latter seems most likely (see also pages 226). However, it will be shown elsewhere (page 229) that siderite replacement was already underway in the ooliths prior to burrowing, so that it is not unlikely that microspar crystals were present in the matrix at the same time.

The resistance of the siderite microsparites to compaction, on the other hand, clearly shows that well developed siderite frameworks were already in existence by the time of compaction, and that variations in grain size and cloudiness are liable to be diagenetic effects. Cloudiness probably indicates that the development of siderite has been retarded, the presence of clear pseudospars that it has been advanced.

5. ,Mode of origin

Hallimond (1925, p. 45) favoured the supposition that the siderite microspar crystals from the Main Seam were in part detrital. He referred particularly to their irregular outline and general distribution in the matrix, but the validity of these criteria is doubtful. Neither the crystal nor the core margins are really distinctive enough to be diagnostic, there being as great a probability that the minor irregularities are diagenetic as original. The general distribution of crystals as shown above, is mainly the product of burrowing and nowhere are there signs of any sedimentary structure which could be used to prove the influence of currents in the deposition of siderite. Only in the Sulphur Band (pages 197- 202) is there any sign of lamination in a siderite mudstone, and here microscopic examination reveals that the siderite is discordant to the laminations which are relict from therreplacement of a laminated shale. Nevertheless there is evidence that some sideritised grains (ooliths, intraclasts and shells) underwent penecontemporaneous erosion so that a small supply of detrital siderite may have been available.

However, there is no doubt that siderite as it occurs in the matrix of the Cleveland Ironstone Seams at the present time is entirely diagenetic in appearance. The occurrence of cloudy cored crystals, whether euhedral or anhedral is typical of replacement or recrystallisation fabrics, as is the overall uniformity of grain size and shape throughout each seam, and the interlocking microspar and pseudospar fabrics.

As regards time of formation the combined evidence from burrows and compaction phenomena indicates thatsiderite growth began soon after deposition, while burrowing was in progress, and was well advanced, and probably completed in most cases by the time compaction occurred. In other words the siderite fabrics as they now exist evolved during early diagenesis, while the matrix was still relatively soft and uncompacted and therefore probably still in contact with the sea water by means of circulating pore waters.

The precise mode of origin, however, depends largely on the form in which iron reached the sea floor (pages 308-312) and upon the shape and gradient of the Eh and pH curves in the sediment (pages 320-326). If siderite was directly precipitated from sea water, in the manner of aragonite in modern limestones, and disseminated through the muds the siderite microspars may have developed by recrystallisation. However, if,on the other hand, the necessary conditions for the formation of siderite only develop below the sediment-water interface, as seems most likely, the fabrics under discussion may be first generation. In either case it is clear that the process of grain enlargement involves the digestion or expulsion of large quantities of clay mineral.

F. SIDERITISATION IN THE CONSTITUENT GRAINS

Siderite is not restricted to the matrix of the ironstones, but occurs in the constituent grains also. It occurs in ooliths, intraclasts, shells and faecal pellets from all the seams to a greater or lesser extent, but is particularly common in grains from the Main, Two Foot and Raisdale Seams. In every instance it is strikingly discordant with the original grain fabrics, and obviously the product of secondary replacement. Crystal size, shape, colour and fabric are, however, distinctly different from the siderite microspars of the matrix in most cases. Only in the faecal pellets and the envelopes of foliaceous ooliths are the cored microspar crystals so typical of the matrix developed.

1. Crystal size, shape, fabric and colour

The crystal size ranges between 0-250μ but average 20-5μ, mainly within the scope of Folk's (1965) pseudospars, therefore. As this name suggests the crystal fabric tends to mimic that of the void filling spars and a similar terminology is applicable ~~(Table —).~~ Although the crystals are frequently stained they may show good crystal faces where they impinge directly upon their host grain, and they share compromise boundaries in aggregate. Isolated crystals, completely enveloped by their host sometimes show perfect lozenge shapes.

However, the development of siderite is greatest at the grain peripheries, and the term 'rind' is introduced here to describe these ingrowths, which are preferentially orientated with respect to the grain surface, in the same manner as crusts or overgrowths externally (Folk 1965). Rinds less than 20-30μ in width usually consist of a single layer of sub equant crystals disposed with their long axes (c-axes) normal to the surface of the host grain, while in thicker rinds a second or third layer of orientated crystals may be added. Towards the middle of the grain however, orientation becomes increasingly random, as crystals growing from different directions impinge.

Where replacement is particularly heavy it may proceed irregularly through the grains picking out minor inhomogeneities such as the laminae of ooliths and shells or cracks in intraclasts. In this way the whole grain may be converted into a mosaic of siderite crystals, but as a rule some relic of the original remains even in cases of extreme sideritisation.

In hand specimen these replacement spars appear brown in colour but their sections reveal variations ranging from colourless through golden brown to dark red brown indicating different degrees of oxidation and also possibly differences in iron content. Although similar colour variations result from recent weathering it must be stressed that the shades referred to here do not result from this cause for they occur in specimens collected fresh both at outcrop and in underground workings. The crystals are usually translucent, although the dark red-brown siderites appear earthy due to the presence of limonite, and may in fact be limonite pseudomorphs after siderite. Cloudiness may also be introduced by the presence of inclusions often arranged in lines and inherited from the internal structure of the host.

2. Sideritised ooliths

The replacement of chamosite ooliths by siderite appears characteristic of minette type ironstones and has been figured and photographed by many authors (see for example Hallimond 1925, p. 122, figs. 1, 3, 4, 5, p. 128, fig. 24; Taylor 1951, p. 81; Davies and Dixie 1951, p. 100, figs. 11, 12; Whitehead et al. 1952, p. 32, fig. 1, 2; Page 1958; Braun 1964, pl. 11, 29, 30, 32; Edmonds et al. 1965, p. 76; Wilson 1966, p. 55). Replacement may be divided into two main types, distinct but passing one into the other. The first consists of a regular cortical layer of siderite which replaces the entire surface of the oolith host and has already been referred to as a replacement rind (plates 24a,d). The second type is much more irregular, and attacks the ooliths patchily either at the margins or at the core or works along interlamina sutures (plates 9a, 24b).

Both types occur in the Cleveland Ironstones but in different facies.

a) Siderite rinds

The most distinctive feature of the siderite rinds is their uniformity; not only do they maintain the same width around the periphery of any one oolith but they remain approximately the same size through a whole thin section, provided the facies is uniform. In different rocks the width of rind varies between about 0-75μ usually a single crystal thick. Taking 500μ as the average diameter for ooliths from the Main Seam, a rock with rinds in the vicinity of 75μ thick shows approximately 50 percent grain replacement; with rinds up to 40μ the figure is about 35 percent siderite (average of the Main Seam, Bottom Block at North Skelton); with rinds up to 30μ, 25 percent siderite (average of Main Seam, Top Block at North Skelton).

That these rinds are secondary after chamosite is proved by the way in which the larger rhombic crystals cut across the chamosite laminae, and also by the preservation of relict textures within the siderite observed both by light and electron microscope (plate
Siderite rinds are sometimes accompanied by isolated crystals of similar size occurring randomly in the interior of the oolith not in apparent connection. They often show good crystal shape and are intermediate to irregular replacement.

Oolith replacement by siderite rind is the usual type in the Cleveland ironstonesseams and exhibits precisely similar characteristics in all the seams where it has been observed (Main, Pecten, Two Foot and Raisdale Seams), ~~(plates~~

b) Irregular replacement

Irregular siderite replacement is a characteristic of ooliths from the Upleatham facies of the Main Seam. Crystal size varies up to about 200μ. Although replacement is sometimes most intense towards the oolith periphery it has proceeded irregularly and may frequently attack the core while leaving the outer laminae unaffected. It has clearly picked out zones of weakness in the oolith. However, even where the carbonate occurs interlaminated with the chamosite, there can be no doubt, because of the way it transgresses the delicate chamosite laminae, that it is of secondary origin. In some cases one half only of an oolith has suffered, in others replacement is total. In consequence euhedral crystals are rare, a mosaic fabric being more important.

In many cases the internal structure of the ooliths is completely destroyed, but in some a relict lamella structure may be preserved ~~(plate)~~. Because the siderite lacks any preferred orientation and also because of straining there is no Brewster cross under crossed polars.

The percentage siderite replacement in the Upleatham facies is higher than in any other, either in the Main Seam or in the minor seams. It averages around 45 percent of the grain total and may reach a maximum of 75 percent.

c) Siderite colour

Wherever siderite occurs as a replacement of the ooliths either as rinds or irregular patches it is golden brown in colour, distinctly different from the colourless siderite of the cement. Thus even where sideritised ooliths are set in a siderite cement it is easy to delimit the original extent of the ooliths. This is strikingly illustrated by Braun's (1964) colour plates 30 and 31 showing irregularly sideritised ooliths which are very reminiscent of those from the Upleatham facies of the Main Seam.(Note also the similarity between the chamosite oolith at the centre of the photographs and the foliaceous ooliths figured in plate 9,10 of this thesis). Where colourless siderite crystals occur in the chamosite ooliths of the Cleveland Seams they appear either to have been intruded during spar collapse (plate 17b) or to occupy shrinkage or fracture cavities developed during early diagenesis (pages 164-167). The colourless crystal which Braun (1964, pl. 31) has described as "a secondary idioblast (growing) into the ooid" seems to be of the latter origin.

3. Sideritised intraclasts

Intraclasts which occur alongside ooliths with siderite rinds behave in much the same way, developing a cortical siderite layer of the same order of crystal size (average 20-30μ) and thickness as in the ooliths, and this in spite of a variation of lithologies ranging from shale to various types of ironstone and in spite of phosphatisation.

Likewise irregular replacement of the ooliths is also accompanied by irregular replacement of the intraclasts. Crystal size varies up to a maximum of about 200μ and is on average larger than in the rind rocks. Replacement is greatest in the more inhomogeneous lithologies. In a mudstone fragment it is often restricted to a narrow irregular rind but incclastic textured types containing ooliths, shells or quartz sand, it encroaches in and around the included grains; similarly if cracks or traces of lamination are present, In a few cases intraclasts have been totally converted to siderite mosaics, but this is unusual. Normally some trace of the original material constituting the grain remains, and the siderite may contain relict structures which facilitate identification even in cases of extreme replacement.

In colour the siderite pseudospars of the intraclasts are identical with those of the ooliths.

4. Calcite skeletal grains

The skeletal debris of animals such as belemnites, brachiopods, ostracods and certain lamellibranchs (for example *Pecten*, and *Ostrea*) all of which preserve their calcite microstructures are never observed to undergo replacement by siderite or any other mineral in the Cleveland Ironstones (pages 135 - 136). Regardless of the amount of breakage and abrasion, fragments which are recognisable as belonging to this group are devoid of the slightest trace of sideritisation and it is therefore concluded that where sideritised shells occur they belong entirely to the aragonitic groups of shells (table 8).

5. Sideritised aragonite shells

The criteria used to infer the presence of aragonitic shells were described in a previous section (pages 134 - 136) where it was noted that aragonite no longer occurs in any of the skeletal debris, having been entirely removed either by replacement or solution. Thus in this instance replacement siderite is frequently associated with secondary voids in the ironstones or with late void filling spars, such as calcite, chalcedonic quartz or sphalerite, formed after the leaching of aragonite.

Two types of siderite occur: the first golden brown, like that of the ooliths and intraclasts, the second colourless like the void filling spars.

a) Golden brown siderite occurs under much the same kind of circumstances as in the ooliths and intraclasts, ranging from narrow cortical rinds to completed replacement mosaics. Once again replacement appears to commence at the grain surface but may work irregularly along lines of weakness such as cracks or more especially the lamella structure. There is a tendency for the crystal size to increase up to a maximum size of about 250μ, away from these growing centres in the manner of drusy mosaic (Bathurst 1958) but the corona effect is less marked (see also pages 178). The compromise boundaries between crystals in the mosaics tend to be irregular, but isolated crystals together with those on the inner surface of the replacement fringes usually show rhombic euhedral shapes. This appears to be an original feature of these replacement spars, but in some cases was probably enhanced by the deposition of a thin coating of colourless drusy spar in optical continuity, following the dissolution of the aragonite. That the majority of the siderite is of replacement origin is proved by the relics of shell microstructures which are preserved within the invading crystals (plate 25b). These are not invariably present, however, and it is clear that in many shells the internal structure was completely destroyed by this process. The behaviour of the siderite rinds and fringes following the removal of aragonite, which takes place after burial (pages 167-168) depends on their thickness. Only the gentlest compaction is apparently necessary to cause the rupture of the thinnest rinds (30μ and below), which are usually displaced into the resultant cavity (see pages 167- 168 and plate 21b). Collapse is much less common in the wider fringes however, which are sufficiently robust to withstand this compaction.

The incidence of golden brown siderite replacement is greatest in large, well rounded shell fragments (coarse sand to granule gravel) which have obviously suffered long and continued abrasion on the sea floor. They stand in distinct contrast to the delicate fragments of thin shelled aragonitic species, which are nearly always replaced by colourless siderite.

b) Colourless replacement siderite is almost identical with siderite cement in these ironstones (pages 176- 180), and may be difficult to distinguish in individual skeletal grains. The crystals are of similar size ( ) and develop corona fabrics in the same manner (page 178). In most cases, because the shells are thin walled, a single layer of crystals growing from opposing walls is sufficient to effect complete replacement. Opposing layers usually meet at an irregular median suture, therefore, but occasionally where a cavity developed following aragonite solution euhedral crystals may occur. (plate 25a)

Despite these similarities many crystals enclose cloudy relics of microlamella structures and some are cored with inclusions, once again revealing idiomorphic stages in the development of replacement spars (cf. pages 217-220).

The shells which reveal this kind of replacement include ammonites, gastropods, scaphopods and the burrowing eulamellibranchs all of which are known as aragonitic types from their modern analogues, as well as a variety of unidentifiable molluscan fragments. All are thin shelled forms and while suffering disarticulation and breakage to varying degrees are seldom at all rounded. The amount of abrasion has therefore been small and it is inferred that this type of shell accumulated under quieter water conditions than those described in the previous section, or underwent more rapid burial.

6. <u>Sideritised quartz grains</u>

The occurrence of sideritised grains believed to be relics of quartz silt and sand grains has been alluded to previously (pages 147, 210). In these too the siderite is colourless and traces of fine grained mosaic fabrics occur. Occasional quartz fragments occur but in most cases the replacement is complete.

7. <u>Sideritised faecal pellets</u>

Faecal pellets are the only grain type which fail to develop pseudospars. They are characterised instead by xenotopic granular microspars identical with those of the matrix, thus underlining the basic similarity in composition between the two. No attempt has been made to estimate the quantitative importance of faecal material in the ironstones for this reason (pages 101, 130-132).

Although there is good reason to suppose faecal pellets provide the nuclei for many ooliths (page 105) these are not affected in the same manner; they either remain unreplaced or in areas of extreme sideritisation develop pseudospars as in the oolitic envelopes.

8. Distribution of sideritised grains in relation to facies

The incidence of grain sideritisation in the Cleveland Ironstone Seams is very variable and quite frequently anomalous with respect to the matrix. For example average values for the percentage grain

$$\text{sideritisation} = \frac{\%\ \text{pseudospar in grains} \times 100}{\%\ \text{grains}}$$

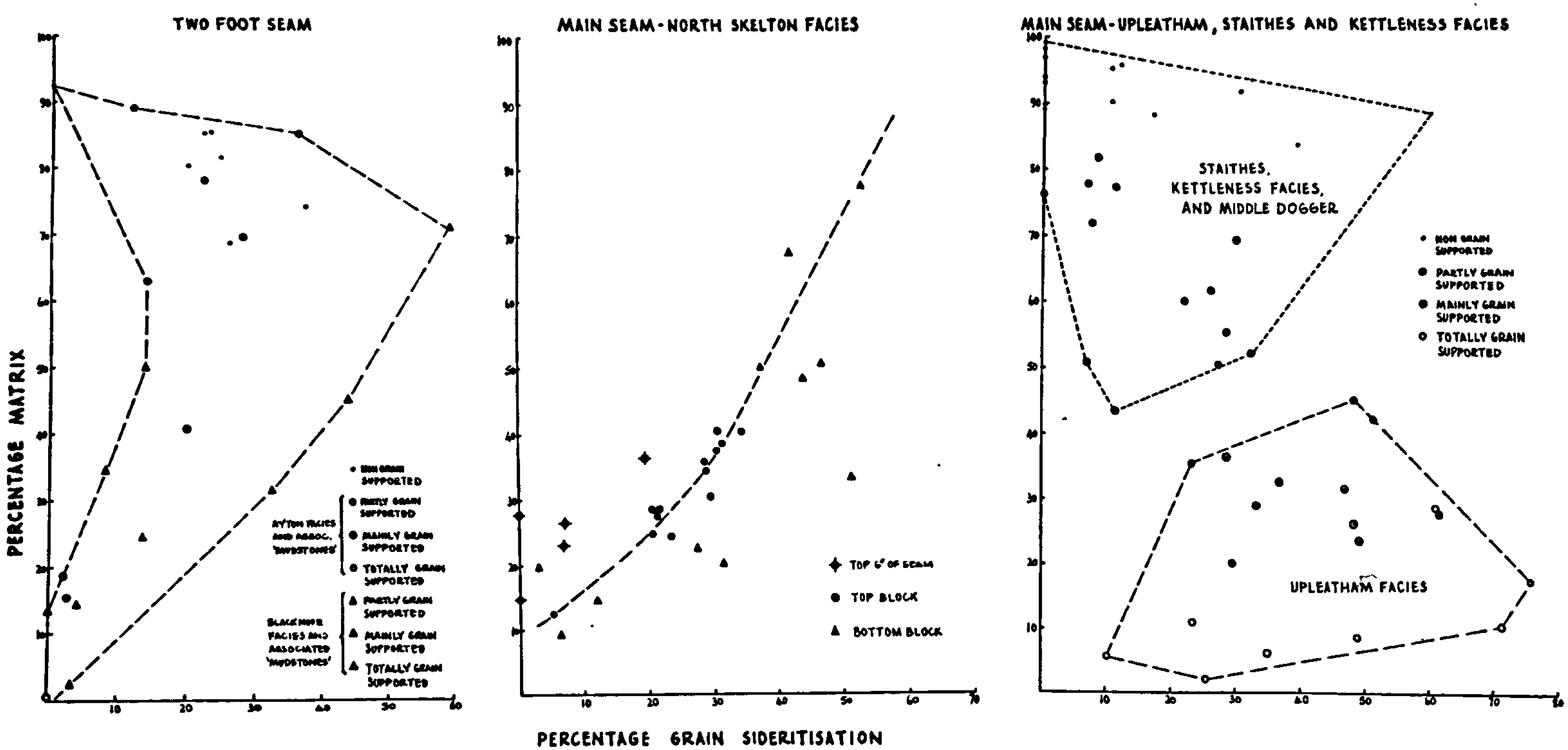
in the Main Seam show that replacement is at a maximum in the shelly intraclastic packstones of the Upleatham facies and falls off steadily in the packstones and wackestones of the North Skelton and Staithes facies, dying out almost completely in the mudstones of the Kettleness facies

packstones	Upleatham facies	average	45%
	North Skelton facies	"	30%
wackestones	Staithes facies (Whitecliff Mine	"	20%
	Staithes facies (Staithes	"	10%
mudstones	Kettleness facies	"	5%

(see also pages 263- 283) ~~and appendix~~).

This is surprising because it is the exact reverse of the situation in the matrix where chamosite dominates in the Upleatham facies and sideritisation is at a maximum in the Kettleness facies (see pages 263, 279).

FIG. 37.



TWO FOOT SEAM
MAIN SEAM - NORTH SKELTON FACIES
MAIN SEAM - UPLEATHAM, STAITHES AND KETTLENESS FACIES
PERCENTAGE MATRIX
PERCENTAGE GRAIN SIDERITISATION
NON GRAIN SUPPORTED
PARTLY GRAIN SUPPORTED
MAINLY GRAIN SUPPORTED
TOTALLY GRAIN SUPPORTED
BLACKMORE FACIES AND ASSOCIATED 'MUDSTONES'
TOP 6" OF SEAM
TOP BLOCK
BOTTOM BLOCK
STAITHES, KETTLENESS FACIES, AND MIDDLE DOGGER
UPLEATHAM FACIES

However, under certain circumstances there does appear to be a positive correlation between the percentage grain sideritisation and the percentage matrix. This is illustrated most clearly by reference to figure 37a whihch relates grain sideritisation to percentage matrix and textural facies in the Two Foot Seam. Considerable variation is present but in general sideritisation is minimal in the grainstone and sparry packstone facies, rises to a maximum in the muddy packstones and wackestones, and then declines again over the wackestone-mudstone boundary.

Insufficient data was obtained to treat the other minor seams in this way but a visual inspection suggests that they conform to the same pattern. However, for the most part mudstones predominate and calcite and kaolinite assume fareegreater importance in grain replacement than siderite.~~(pages~~

The Main Seam, however, shows considerably more complexity (figure 37b,c), partly because of the intercalation of the Upleatham facies and partly because of variable grain sideritisation in the wackestone facies. As with the minor seams the percentage grain sideritisation is low in the mudstone facies and on average tends to increase in the wackestones ~~(page ——)~~, although no clear trend emerges from figure 37c Similarly the scatter of analyses in the packstone and grainstone facies appears completely random.

However, a more detailed examination of the packstones and wackestone of the North Skelton facies in the Top and Bottom Blocks at Lumpsey and North Skelton Mines does reveal a positive correlation between the percentage matrix and the percentage grain sideritisation, similar to that in the Two Foot Seam. In other words it is the presence of the Upleatham facies which confuses the situation. Among all the ironstone facies this is unique for its extreme and irregular sideritisation; particularly remarkable in view of its green chamosite mud matrix. However, the facies is peculiar in other respects as well, and not least in its shelly intraclastic texture and in the occurrence of cross bedding. The mixture of sideritised grains, sometimes broken, with unsideritised grains and the presence of intraclasts and well rounded shells suggests that these deposits are reworked, which may explain the anomaly in part (see also pages 263-267)

9. Time and mode of origin

The fundamental difference which exists between the golden yellow and colourless siderite replacement spars indicates at least two phases of siderite replacement. Although the two types are differentiated between various grain types, the participation of both in the replacement of aragonite shells proves that colour is not merely the result of differences of original grain mineralogy. Even where the two occur together in the same shells the evidence for their time relations is equivocal and therefore their relative ages have to be sought indirectly against the background of the other diagenetic changes taking place.

a) Golden yellow siderite occurring both as rinds and irregular replacement mosaics is plainly early diagenetic in origin (cf. Taylor 1949, p. 19). Like the ooliths, siderite rinds are ruptured during compaction, and sometimes even earlier, apparently as the result of the passage of burrowing animals through the soft sediment. Sideritisation therefore took place either at the sediment water interface or within the superficial sediment shortly after burial. The general uniformity of the siderite rinds in many rocks together with the absence of rinds on broken ooliths which occur as the nuclei for later ooliths favours the latter, but in cases where the sideritisation is irregular both with respect to the individual grains and the grain framework as a whole replacement on the sea floor or alternatively the reworking of older deposits is postulated. The juxtaposition of sideritised and unsideritised ooliths in the Upleatham facies is interpreted as the result of such reworking (cf. Hatch et al. 1938, p. 135). The irregularity of replacement within the ooliths may indicate that some have undergone several phases of reworking and sideritisation, for it is clear that the mode of origin differs from that of the rindooliths.

In the light of the oxidation-reduction requirements for the precipitation of siderite (fig.40b) it seems unlikely that this mineral could develop directly at the sediment water interface, especially under the high energy conditions invoked for the Upleatham facies (page 265) and it is therefore probable that sideritisation only takes place after burial.

The yellow brown colouration of the mineral, which is so uniform in these siderite spars, probably results from small quantities of ferric iron being incorporated at the time of replacement rather than from subsequent oxidation. However, where reworking has taken place it is possible that the colouration developed through oxidation on the sea floor. Certain limonite pseudomorphs after siderite from the Upleatham facies appear to result from this cause, but unfortunately these have only been observed in specimens collected at outcrop below Hob Hill and it is difficult to evaluate their importance against the background of recent weathering. Rather surprisingly specimens from the Upleatham facies in the Survey collection ~~(appendix)~~ failed to reveal evidence for this phase of limonitisation although they indicate considerable reworking (Hallimond 1925, p. 48).

The time relations of the golden yellow siderite pseudospars are similar to those of the siderite microspars of the matrix (pages 215-216) so that it is probable that both form as part of the same diagenetic process. The effects of this process are however different not only in regard to texture but also relative intensity. Ideally one might expect the degree of grain sideritisation to increase in the passage from chamosite grainstones to siderite mudstones, but while this has been deduced to apply in certain grainstone-packstone facies (figs. 37 a,b) various anomalies have been pointed out, and in particular the tendency towards reduced sideritisation in grains from the wackestone-mudstone facies. No simple relationship between percentage grain sideritisation and percentage matrix exists.

Considering the sensitivity of the sideritisation process this is not surprising. Thermochemical work (Krauskofp 1957, p. 64, Garrels and Christ 1965, p. 228) indicates a fairly restricted field over which siderite formation takes place requiring a stringent set of conditions including:-

(i) available iron

(ii) reduced Eh

(iii) mildly alkaline pH

(iv) high concentrations of CO_2

(v) low concentrations of silicon ions

(vi) low concentrations of sulphur ions

(see pages 317- 319 and figs. 40 a, b).

Even minor variations between grains and matrix with respect to factors (i)-(v) would affect the relative stabilities of chamosite and siderite and be reflected by differences in relative replacement.

The ratio of matrix to pore space during early diagenesis is clearly important because it determines the extent to which pore water is able to circulate and therefore the oxygenation of the deposit, but the matrix is also important because it contains faecal debris which offers a possible source of CO_2. Wherever a positive correlation exists between matrix and grain sideritisation these two controls appear to be of prime importance.

The anomalously high grain sideritisation of the Upleatham facies has been partly explained as the result of reworking, but if the process took place ' in situ' may reflect the intervention of other controls, which cannot be specified. The decline in grain sideritisation in many wackestones and mudstones may be explained by a tendency for the ooliths to be leached of iron. In consequence they are more prone to replacement by minerals like calcite and kaolinite than by siderite (see pages 239, 244).

b) The colourless siderite replacement spars appear to have developed simultaneously with the siderite cements. Apart from their mode of emplacement the two are petrographically identical. They certainly postdate the golden yellow pseudospars because they have been observed in replacement of limonite pseudomorphs after the latter.

They occur in grains which resisted the first phase of siderite replacement, mainly aragonitic shells and quartz grains, subject to the same kind of conditions as those specified above (page 232) Not surprisingly siderite pseudospars of this type are restricted to rocks containing void filling siderite.

10 Conclusion

As in the case of siderite cementation (pages 176-180) siderite replacement is of considerable economic importance because it offers a means by which chamositic ironstones may be enriched in iron during diagenesis. It was Sorby in 1857 who first drew attention to the importance of this enrichment, being particularly impressed by the evidence of replacement in ooliths and shells; he also recognised that the incidence of sideritisation was greater in aragonite than in calcite shells and went on in 1906 to publish the results of further observations and experiments on shell replacement. The material upon which he worked in 1857 must have been largely derived from the Upleatham facies of the Main Seam from the Eston and/or Upleatham royalities (see pages 263-268) where grain sideritisation is spectacular. Hence he was led to the general conclusion that "at first, the Cleveland Hill Ironstone was a kind of oolitic limestone interstratified with ordinary clays containing a large amount of the oxides of iron and also organic matter, which, by their mutual reaction, gave rise to a solution of bicarbonate of iron - that this solution percolated through the limestone, and, removing a large part of the carbonate of lime by solution, left in its place carbonate of iron; and not that the rock was formed as a simple deposit at the bottom of the sea."

This, the limestone replacement theory for the origin of the Cleveland Main Seam, and minette type ores in general, stood for nearly seventy years before it was positively challenged by Hallimond (1925, p. 48) who demonstrated the importance of the mineral chamosite to an understanding of the origin of the bedded ores of England and Wales. The present work like a large body of previous work supports Hallimond's contention that replacement siderite is largely derived by the carbonation of pre-existing iron minerals. (Hallimond 1925, p. 21-22).

C. SILICIFICATION

"The Cleveland ooliths are often peculiarly white in hand specimen and appear in thin section to contain semi-opaque bands which are snow-white by reflected light .... apparently due to a slight alteration, with formation of finely divided silica or clay" wrote Hallimond (1925, p. 45) in describing the Main Seam. The whiteness in hand specimen has indeed been attributed to two main causes:-

(i) kaolinitisation (Dunham in Whitehead et al. p. 26), which will be discussed subsequently.

and (ii) replacement by opal (Dunham op. cit. p. 24).

However, it may also result partly from the fine grained powdery nature of the chamosite since many ooliths appear white in hand specimen without any indication of alteration in thin section.

The presence of opal as a replacement mineral appears to be confirmed both by chemical analysis (Dunham loc. cit.) and by x-ray examination (Bannister in Whitehead et al. 1952, p. 20), although a comparison between green and white ooliths during the present work failed to reveal any noticable difference in x-ray powder photographs. Only when ooliths were treated in hot dilute hydrochloric acid was a recognisable halo produced extending from 4.6-3.5Å and centred at about 4Å (cf. Bannister op. cit. p. 32). This confirms the implications of the work by Dick (1886) and Stead (1910) that chamosite ooliths are leached of iron and alumina by the action of hydrochloric acid and break down to an impure silica gel. It is therefore incorrect to equate the 'siliceous envelopes' of Stead (op. cit.) directly with the opaque, white reflecting layers seen in thin section. It is also dangerous to rely on any material produced after the treatment of chamosite with acid, even cold dilute hydrochloric acid because of the possibility of silica being liberated in the laboratory (see Yoûell in Dunham 1960, p. 248).

White-reflecting semi-opaque bands occur in ooliths from several seams (Main, Two Foot and Raisdale Seams) but are particularly common in the North Skelton facies of the Main Seam (pages 268- 273). from which Dunham derived his specimens. This type of alterations also occurs in intraclasts but it is in the ooliths that it is most prominent. It is especially noticable in ooliths which have undergone heavy replacement by siderite rinds, but not where irregular siderite replacement has taken place (pages 220- 221), which explains why opacity is more common in the North Skelton facies than in the Upleatham (pages 263- 267). Some ooliths show alternations between opaque mineral and more or less unaltered chamosite in which case it appears that the unorientated chamosite has suffered more than the orientated which still produces a black cross under crossed polars (pages 109-111) Many ooliths, however, are opaque throughout and very little differentiation of structure is possible. Occasionally the opaque material is broken by septarian type cracks infilled with isotropic cryptocrystalline chamosite. (plate 24d)

Opacity is considerably reduced where slides are ground finer than 30μ to reveal a cloudy colourless cryptocrystalline or amorphous material, probably consisting of a mixture of chamosite with opal, virtually isotropic under crossed polars but with some vestigial birefringence. Dunham (op. cit.) considered that this opacity might result from a small percentage of TiO_2 perhaps in conjunction with ultramicroscopic clay particles in the opal. However, the development of opacity has been found to be somewhat dependent on the vagaries of section making; the thickness of the slice, the amount of heat applied, and the mounting media used are all important. Both chamosite and opal absorb a quantity of water, which is driven off when sections are mounted on a hot plate. It is possible therefore that the opacity may be induced by the presence of ultramicroscopic water vapour bubbles either trapped within the minerals or between the minerals and the mounting media. Disastrous results were obtained when thin sections were secured by a thin film of Durofix prior to being coverslipped; without exception the ooliths turned opaque and reflected white, apparently as a result of the development of a layer of bubbles at the interface between the clay minerals and the Durofix.

Although opacity may be taken as an indication of the presence of opal in an oolith or in an oolith or intraclast, it is impossible to determine precisely how much is present because it is probably intermixed with cryptocrystalline chamosite. In most cases the percentage must be small; too small to be identified consistantly on x-ray powder photographs.

The association between opal and ooliths with well developed siderite rinds suggests that silicification may result as a by-product of sideritisation. In other words the process by which iron is leached from the ooliths to form siderite may be similar to process of leaching in acid. It is even possible that acid solutions played a part during diagenesis judging from the evidence of solution collapse in the ooliths cited earlier (page 165). In the former case opalisation classified as an early diagenetic effect, in the latter as a late since sideritisation and solution collapse are so dated.

Late diagenetic silica is also introduced in the form of anhedral quartz replacement spars in the Main Seam, mainly developed at the expense of ooliths and intraclasts. The crystals reach an average size of about 300μ and form mosaics closely resembling void filling quartz except for the presence of inclusions (page 191). Also whereas drusy mosaics are usually comprised of chalcedonic quartz, replacement mosaics show crystals with plane extinction. The two types occur together in the same grains in some instances, and it is clear that they formed contemporaneously, in a similar manner to replacement and drusy calcite spars in shells. In places quartz may result from the crystallisation or redistribution of opaline silica, but the majority is probably derived from outside the Main Seam. ~~(page~~

H. KAOLINITISATION

The devèlopment of kaolinite as a replacement mineral was recognised by Duhham (in Whitehead et al. 1952, p. 26) on the basis of optical determinations, which are confirmed in this work by x-ray powder data. The mineral is fairly common in all the seams, although it is rarely present in amounts more than 5 percent, and occurs mainly as a replacement of the allochems: ooliths, intraclasts and to a lesser extent aragonitic shell debris.

In hand specimen the mineral is often identifiable by its chalky white appearance. In thin section it is colourless but may be cloudy depending upon the crystal size; there is an overall range in size between cryptocrystalline and finely mesocrystalline (page 244). Large crystals reach a maximum size of about 100μ and occur as vermicular prisms with perfect basal cleavage, but the average size is around 5-10μ (microcrystalline); below 4μ the mineral appears cloudy and isotropic and may be heavily stained with brown hydrocarbon (cf. Rastall and Hemingway (1939)) in which case it is only identifiable from x-ray data.

Replacement is very destructive leaving no trace of relict textures within the crystals so that replacement mosaics, consisting of equant euhedral crystals with characteristic 'rouleau' structure, are identical with those found in septarian cracks and it may be difficult to decide whether one is dealing with a void filling or replacement spar in some cases. This is especially so with kaolinite pseudomorphs after aragonite shells because all trace of the original structure has gone. However, ooliths and intraclasts occur in all stages of replacement with mosaics which are either distinctly discordant with the pre-existing structures or develop from them via a zone of cryptocrystalline material. The balance of probability therefore favours a replacement origin wherever kaolinite occurs in the allochems. There is no evidence whatever to suggest that it was a primary constituent of the ooliths, although it was undoubtedly present in some of the intraclasts from the start. (plate 28d).

The question therefore arises as to the origin of the mineral. Although it sometimes occurs in grainstone and packstone facies it is in the wackestone and mudstones that it is most common. Except for occurrences in septarian cracks it is always restricted to the allochems and most abundant in the ooliths; it never occurs as a replacement of the matrix. This suggests the possibility that kaolinite could be derived, by the 'in situ' breakdown of chamosite following the leaching of iron to form the siderite microsparites, by an intensification of the process which leads to the formation of opal.

However, the presence of kaolinite in aragonitic shell debris and septarian cracks indicates some mobilisation and redistribution of the mineral, and in detail this hypothesis breaks down. Whereas the siderite microspars formed prior to, and during the early stages of compaction, kaolinite is judged to post-date the main phase of compaction since it lacks all sign of deformation (see fig. 38).

The mineral cannot have developed as a direct result of sideritisation, therefore, although it is possible that indirectly the presence of leached chamosite may have favoured the introduction of kaolinite. The most likely source for the mineral lies outside the ironstones in the kaolinitic shales associated with the seams, from which large quantities could have been derived during the process of compaction.

Although kaolinite is classed as late spar it predates the main phase of calcite deposition being replaced by the latter both in septarian cracks and aragonite shell debris.

I. DOLOMITISATION

Hallimond (1925, p. 45) reported that in the matrix of the Cleveland Main Seam "the siderite crystals include minute parallel rhombs of dolomite", but the present work has failed to yield confirmation on this point (page 209). However, dolomite has been encountered, mainly as a replacement of allochems, from the Two Foot Seam in the Blackmore area and also from the Grosmont Pecten Seam at Hawsker.

In the former the mineral occurs as colourless anhedral or subhedral crystals up to a maximum size of about 400μ but averaging 100-200μ (fine-medium mesocrystalline, page 244), with pronounced spectral or spherulitic extinction (plate 29d). Relief is high and the mineral shows curved cleavages, and crystal faces when developed. Its identity was checked both from x-ray powder photographs and by staining which indicated a non-ferroan variety. By comparison the dolomite from the Pecten Seam is microcrystalline and proves to be a ferroan variety. It is a relatively unimportant diagenetic constituent, here, but in the Two Foot Seam it occurs in amounts up to 10-15 percent (20-25% of the grain total).

As with siderite the dolomite from the Two Foot Seam shows a tendency to form replacement rinds, but generally it occurs in random mosaics, which may be strikingly displacive within ooliths and intraclasts. Normally this displacement is contained within the grains, especially in the presence of a muddy matrix, but in some cases where an aragonite cement existed, the outer laminae of the oolitic envelope sprang open, or the oolith was split in two separate parts, or disrupted in some other way (plate 29c). Presumably the aragonite spars were less resistant to the force of dolomite cyrstallisation than the matrix.

That an aragonite cement was in existence prior to the growth of dolomite is proved by the following:-

(i) In spite of severe disruption there is no evidence of broken ooliths having fallen loose into open intergranular pores; rather the cement appears to have retained and supported the displaced fragments.

(ii) In some instances dolomite was seeded at the surface of the ooliths (i.e. on the cement) and displaced the oolitic envelopes inwards.

The rupturing of the ooliths must therefore have been attended by breakage in the aragonite cement, relics of which remain pseudomorphed by calcite, but unfortunately the latter replacement renders the details of the aragonite spars obscure.

Dolomite therefore postdates aragonite and also early diagenetic siderite, since siderite rinds were already developed on the allochems prior to dolomite replacement. In addition in one small void siderite spar was found to be euhedral to a later filling of dolomite. The mineral therefore classified as a late diagenetic spar although it appears to predate calcite where the two carbonates occur together in the same allochem.

J. SPHALERITE REPLACEMENT

The occurrence of sphalerite as a void filling spar has already been noted (page 190). Not infrequently this is accompanied by a small percentage of replacement sphalerite often optically continuous with the void fillings (see plate 23d for example), and therefore difficult to distinguish in many instances.

The most spectacular example of sphalerite replacement occurs in the top six inches of the Main Seam where plates of the mineral up to an inch across occur in replacement of large shale and mudstone intraclasts (see also Tate and Blake 1876, p. 119). However, the mineral has also been observed as a replacement in intraclasts and ooliths from the Two Foot and Raisdale Seams. Optically it is indistinguishable from the void fillings and it is clear that replacement and drusy filling were taking place simultaneously as in the case of other spars.

K. CALCITE REPLACEMENT

Calcite replacement may take place in grains and matrix regardless of their mineralogy, both at the expense of the original constituents and pre-existing diagenetic spars. A complex series of diagenetic modifications results, occupying a major role in the paragenesis of all the ironstone seams. Both ferroan and non ferroan spars participate but the latter is subordinate accounting for less than one percent of the total. The potassium ferricyanide stain, in association with alizarin red S has therefore proved invaluable in gauging the extent and intensity of replacement.

1. Crystal colour, size, shape and fabric

By comparison with other replacement spars calcite is very variable in character. Macrocrystals appear chocolate brown in hand specimen, but the mineral may be either pale brown or colourless in thin section in the same manner as the calcite cements. Crystal size varies very irregularly over a range extending from a few microns to a few millimeters and the following classes and terms have been adopted:-

macrocrystalline		$>$ 2 mm.
mesocrystalline	coarse	0.6 - 2 mm.
	medium	0.2 - 0.6 mm.
	fine	0.06- 0.2 mm.
microcrystalline		0.004-0.06 mm.
cryptocrystalline		$<$0.004 mm.

The terms cryptocrystalline, microcrystalline, mesocrystalline and macrocrystalline have been made conterminous with Wentworth's (1922) clay, silt, sand and gravel classes respectively, although this represents a departure from previous usage (see Pettijohn 1957, p. 93). All size values refer to the average major dimension of the crystals.

Unlike siderite, calcite never forms euhedral crystals, nor does it show any preferred orientation with respect to the existing rock framework in most instances; it occurs as ragged random mosaics consisting of equant anhedral crystals frequently with pronounced spectral extinction, or as single crystal plates mimicing replaced grains.

2. Calcite replacement in the matrix

Calcite is particularly variable where it occurs in replacement of the matrix. Crystal sizes range from cryptocrystalline, in which case the mineral is only identifiable by staining, through microcrystalline to coarsely mesocrystalline. Differences in colour and intensity of stain indicate variations in iron content, but the true colour of the mineral is often difficult to ascertain due to the presence of abundant cloudy inclusions.

The mesocrystalline mosaics, especially those which are coarse, reveal crystals with exceptionally ragged, interpenetrating grain boundaries, and marked spectral extinction, sometimes bordering on spherulitic. The former clearly reflects the irregular manner in which calcite invades the fine grained inhomogeneous material which constitutes

PLATE 28. Calcite and kaolinite replacement

a) Ooliths replaced by calcite. Osmotherley Seam, Hawsker. (Note burrowing).

b) Poikilotopic calcite replacing ooliths, shells and matrix. Main Seam, Kettleness. ((Crossed polars).

c) Spherulitic calcite replacing intraclast. Main Seam, Staithes. (crossed polars).

d) Microcrystalline kaolinite replacing ooliths and gastropod shell (crossed polars).

x ~~100~~ 30

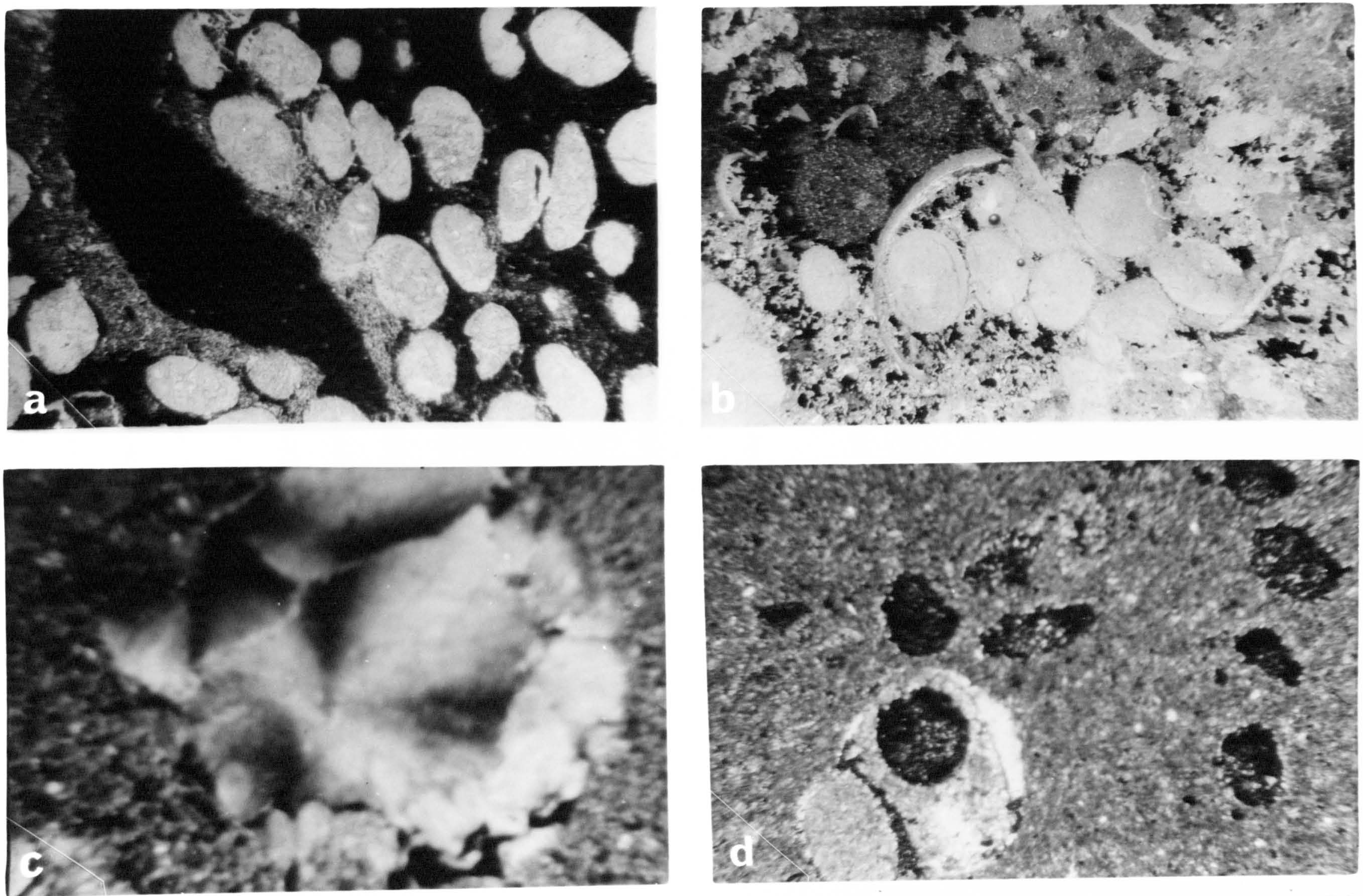


PLATE 28

the matrix. Siderite, phosphate, chamosite, detrital clay minerals and quartz all suffer in the process, but in differing ways. The finer grained material, mainly clay mineral, undergoes attack first but always leaves a spar clouded with ultramicroscopic inclusions; siderite is slightly more resistant especially where it occurs as coarse grained microsparites (page 208) and leads to clearer calcite mosaics, while quartz silt grains although coroded superficially are the most resistant and often occur poikilotopically enclosed by calcite.

Calcite emplacement is observed to take place in the following stages:-

(i) mineral attacks along siderite grain boundaries and incipient cracks, anastomosing to form a complete network.

(ii) the network is enlarged by further replacement leaving small islands of the original matrix 'floating' in calcite

(iii) eventually these islands are eliminated and calcite invasion is complete, although relics of depositional texture are preserved as cloudy inclusions (plate 12c).

(iv) depending on the intensity of replacement these inclusions may also be eliminated to a greater or lesser extent.

The variation in crystal size already noted is probably mainly dependent upon the grain size, porosity and composition of the matrix undergoing replacement. Thus finegrained argillaceous siderite mudstones are replaced by cryptocrystalline or microcrystalline mosaics analogous with those occurring in sideritic calcite mudstone nodules formed by the replacement of shales ~~(pages)~~. Mesocrystalline mosaics with maximum observed grain sizes of about 1.2mm. develop under more favourable conditions:-

(i) where the original grain size, and packing of the matrix was such as to give a high porosity.

(ii) where calcite was formed by the replacement of pre-existing aragonite replacement spars.

(iii) where shell debris with mesocrystalline internal structures (i.e. belemnites) occurred in the matrix; these provide the only substrates where syntaxial replacement overgrowths occur.

3. <u>Calcite replacement of aragonite spars</u>

The reasons for supposing that aragonite once formed a significant part of the early daigenetic spars, both void filling and replacive, have already been given (pages 181 - 184 and 205). The process whereby aragonite replacement spars in the matrix are converted to ferroan calcite has been mentioned above and the following paragraphs refer rather to the replacement of void filling aragonite.

Both ferroan and non-ferroan calcites occur as replacements of these spars. The ferroan variety is usually colourless in thin section and stains light blue by contrast with the dark blue of the high iron calcites; it forms microcrystalline to fine mesocrystalline anhedral mosaics of equant crystals with only occasional bladed pseudomorphs. Characteristically these calcites are clouded with inclusions which may preserve the acicular columnar or radiating habit of the original aragonite (page 182). In this case there can be no question of a straight inversion between aragonite and calcite because of the introduction of iron into the structure. Non ferroan calcite is stained pink in thin section and here there is a possibility of inversion. This variety forms perfect pseudomorphs after aragonite, although usually comprising a mosaic of crystals rather than a single crystal. It always occurs in association with ferroan calcite and is often in optical continuity.

The nature of the juxtaposition of these carbonates indicates that the non ferroan calcite postdates the ferroan, especially in view of the occurrence of relict aragonite partly corroded by non-ferroan mineral. (pages 181 - 182 and plate 22d).

4. <u>Calcite replacement of aragonite shells</u>

A certain amount of difficulty arises in distinguishing aragonite shell pseudomorphs formed by replacement from those formed by solution-fill, (pages 187, 172); only when relics of internal structure are present can one be certain one is dealing with a replacement spar (pages 173). These relics take the following forms:-

(i) preservation of internal microstructure by lines of inclusions (plate 13b),

(ii) presence of straight or slightly curved intergranular boundaries, forming continuous or discontinuous lines through the calcite mosaic, and indicating original lamella structures (plate 13b).

PLATE 29.

a) Recrystallised acicular bundles of chamosite (see also plate 18d) Avicula Seam, Staithes. x ~~100~~. 30

b) Colloform phosphate associated with shell debris. Two Foot Seam, Staithes. x ~~90~~. 30

c) Chamosite ooliths (Hydrocarbon stained) replaced by dolomite. Note disruption of oolith lower centre. Two Foot Seam, Glaisdale. x ~~200~~. 70

d) Spherulitic dolomite replacing ooliths and shells. Two Foot Seam, Bransdale x ~~90~~. 30

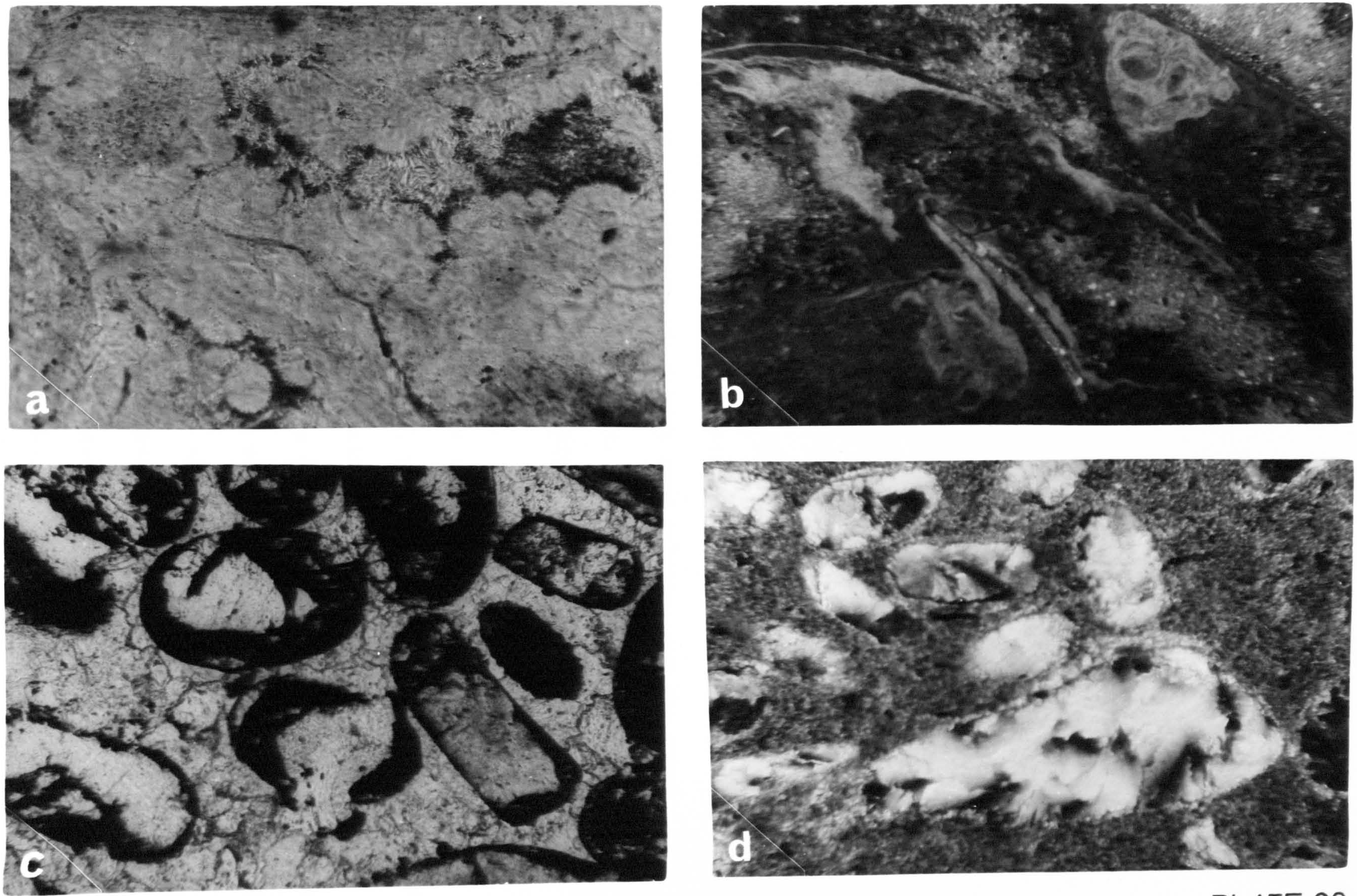


PLATE 29

(iii) Some spars appear dark brown in thin section due to the presence of inclusions, and may show slight pseudopleochroism (Hudson 1962); this colouration must not be confused with the paler more uniform brown indicative of high iron calcites.

High iron calcite is the dominant replacement spar, although low iron calcite also participates in the Two Foot Seam; non-ferroan calcite never occurs. The former develops medium to coarse mesocrystalline mosaics; consertal but not ragged. The individual crystals are equant and anhedral, show curved cleavages and undulose or spectral extinction, and are mainly discordant with the relics of internal structure. Except for the occurrence of relict shell structures these spars are identical with drusy fillings composed of high iron calcite, and the conclusion must be that they are of similar age, that solution-fill and replacement were active at the same time, even within the same shells. (see ~~fig~~. plate 21c and pages 189-190).

Low iron calcites, which occur as single plate rather than mosaic pseudomorphs after aragonite shells, seem to arise mainly as a result of void filling (pages 189); extinction is usually straight but may be slightly spectral although not to the same degree as in the high iron calcites. However, in the Two Foot Seam these same crystals may contain relict shell microstructures. Once again it appears that void filling and replacement took place simultaneously.

As pointed out previously (pages 189-190) the question of calcite paragenesis is complicated by the difficulty of determining precisely how many phases of calcite emplacement occur in each seam and to what extent they may be correlated between seams, a problem which will be discussed again later (pages 255).

5. Ferroan calcite replacement of calcite shells

It is most unusual for calcite skeletal debris to undergo either replacement or recrystallisation in these rocks, internal microstructures being perfectly preserved. However, staining has revealed incipient replacement to ferroan calcite in one of two instances. For example the macrocrystalline fibrous structure of some belemnite guards has been degraded to medium mesocrystalline ferroan calcite, while occasional specimens of Pecten and Ostrea, show cryptocrystalline ferroan calcite working along the lamella boundaries.

It is significant that wherever this process is taking place iron is being introduced into the lattice so that replacement is a more appropriate term than recrystallisation.

6. Calcite replacement in ooliths

Both Hallimond (1925, p. 47) and Dunham (1951 and in Whitehead et al. 1952, p. 28) have shown that although calcite occurs in the ooliths it is the result of replacement and not a primary mineral as postulated by Sorby (1857, 1906) and Stead (1910). Ooliths replaced by calcite occur in every seam and all stages in the conversion of chamosite to calcite may be observed. Although replacement may sometimes attack along the laminae of the ooliths or at the nucleus, seeding is generally random, there being no attempt, as in the case of siderite, to form calcite rinds.

The calcite is usually of the brown, high iron variety and occurs as medium mesocrystalline plates and mosaics even where the groundmass may be microcrystalline low iron calcite after aragonite. Depending on the crystal size two or three crystals may be present in an anhedral equant mosaic, but frequently a single crystal suffices to replace one oolith or a group of ooliths in close proximity. In this way macrocrystals up to about 5 mm. across may develop, either passing directly from oolith to oolith in point contact, or enclosing the intervening matrix as well (plate 28b)

Because therreplacement is very destructive many calcitised ooliths lack all trace of original structure, but under certain circumstances, through the segregation of impurities, relict textures may be retained even where chamosite has been entirely removed (plate 28a)

7. Calcite replacement in intraclasts

Intraclasts undergo calcite replacement in the same way as other grains but with a greater diversity of crystal habit because of the variety of lithologies; mudstone intraclasts react in much the same manner as the matrix while oolitic intraclasts share features in common with replaced ooliths. However in one particular instance (at the top of the Bottom Block of the Main Seam at Staithes) intraclasts from a variety of lithologies, including mudstones and oolitic wackestones, are replaced by a most distinctive spherulitic calcite. The spherulites reach a maximum size of about 4 mm. and are composed of radiating fibrous crystals of high iron calcite which give a characteristic black cross under crossed polars. (plate 28c)

8. Distribution of calcite replacement spars

Although replacement calcite occurs in all seams its distribution is rather irregular and appears to depend on a number of factors including:-

(i) the distribution of skeletal debris and particularly aragonitic skeletal debris.

(ii) the distribution of early diagenetic aragonite spars.

(iii) the relative stability of minerals pre-existing in the constituent grains and matrix.

(iv) the permeability of the rock at the time of calcite emplacement.

The distribution of aragonite is important not only because it is readily converted to calcite but because an increase in volume of 8.7 percent is involved, so that excess calcium carbonate is available both for void filling and replacement. In addition solution collapse, accompanied by compaction, provides an excess of carbonate ions, so that it is not surprising that shell beds and lenses in the ironstone seams become centres for calcite replacement; not only the shells are replaced but ooliths, intraclasts and matrix as well.

Calcite replacement therefore reaches a maximum in the grainstone and packstone facies of the Two Foot and Raisdale Seams where there is abundant aragonite both in the shell debris and in theearly diagenetic cements. Staining reveals concretionary calcite masses in both these seams, in which invasion reaches 90% although the absolute percentage of calcite is probably around 80% accounting for inclusions. No compaction is involved around these concretions except where they were primarily aragonite in which case compaction took place before rather than after calcite emplacement (pages 184). The boundaries are usually sharp, delineated by the included shells; on one side of a shell replacement may be minimal, while on the other it may be virtually complete. It is therefore possible to trace calcite 'fronts' through thin sections, sharp where they coincide with skeletal debris, slightly diffuse where they pass through grains and matrix between neighbouring shells. Even within concretions the intensity of calcitisation may vary strikingly in areas delimited by large shells.

The Pecten Seam although equally fossiliferous does not develop such concretionary masses, possibly because calcite shells predominate over aragonite, but more likely because of the difference in lithology; the seam consists of siderite mudstones and chamositic shales of low porosity by comparison with the previous seams which were still incompletely cemented at the advent of calcite deposition (page 189).

Although the packstone facies of the Main Seam resemble the grainstone-packstone facies of the Two Foot and Raisdale Seams in many respects calcite does not occur as a replacement mineral, despite its occurrence in some secondary voids (page 267). There may be several reasons:-

(i) Aragonite shells were less common and underwent replacement to siderite rather than to calcite (page 225). Since all the available carbonate ions were being utilised to form siderite cements at this time calcium was probably lost in solution.

(ii) At the completion of this cementation intergranular porosity was virtually eliminated, leaving no room for calcite cements, and hindering solutions capable of replacement.

(iii) No aragonite spars developed in the grain rich facies of the Main Seam (pages 263- 273).

Calcite replacement does occur importantly in the grain poor facies of the Main Seam (wackestones and mudstones) and in similar rocks from the other seams. However for the most part it is the grains which suffer rather than the matrix, and not only the aragonitic shell debris but the ooliths also. In the passage from wackestone to mudstone, the percentage of chamosite in the ooliths falls off rapidly until in the mudstone facies it disappears altogether, having been converted either to calcite or kaolinite. This applies in every seam so that apart from differences in oolith shape (page 118) it is difficult to distinguish between oolitic siderite mudstones taken from different horizons.

Whereas calcite replacement is general in grains from mudstone facies, it is exceptional in the surrounding siderite microsparites being restricted to areas of calcite concretion in shelly lenses previously enriched in aragonite.

From the above the following tentative conclusions are drawn:-

(i) that chamosite is less resistant to calcite replacement than siderite.

(ii) that chamosite is more stable in grainstone and packstone facies than in wackestone-mudstone facies, where iron may well have been leached from the ooliths in order to supplement the sideritisation of the matrix (see also pages 238).

9. Paragenesis

Calcite occurs in replacement of chamosite, siderite microsparites, aragonite, and kaolinite and is therefore classed as a late diagenetic spar in the same way as the calcite void fillings. In many cases void filling spars and replacement spars occur in close association and are so similar that they must be contemporary. Both high iron and low iron calcites are present, but how far these may be correlated with the analogous void fillings is difficult to say. In the Two Foot Seam, there are replacement spars corresponding with both the phase (ii) and phase (iii) void fillings but how much replacement was accomplished during phase (i) is not known.

The overall abundance of calcite and the indication of several phases of replacement suggests that the mineral was available over long periods of time, possibly extending into the Quaternary.

VII DIAGENETIC HISTORY

A. GENERAL STATEMENT

As with many chemical sediments the diágenetic history of the Cleveland Ironstone Seams is complex, and yet the outstanding feature which emerges from a comparison between the various seams is the similarity of paragenetic sequence. In each case paragenesis is effected by two most important events; the first, burial and the second, siderite cementation. These provide a relative scale against which other diagenetic modifications can be measured as follows:-

(i) Halmyrolysis - diágenesis before burial or submarine weathering.

(ii) Early diagenesis - modifications taking place after burial up to and including the precipitation of siderite cement.

(iii) Late diagenesis - modifications taking place subsequent to siderite cementation.

Whereas it is possible to date burial in stratigraphic terms it ismuch more difficult to date cementation and therefore to say at what time early diagenesis ended and late diagenesis began. Furthermore diagenesis is like a cell which expands with time; during halmyrolysis modiciations arise as a direct result of interactions at the sediment water interface while during the following phases of diagenesis increasing thicknesses of strata are liable to be involved, more minerals become available, and the possible diagenetic modifications become more numerous. The main differences between early and late diagenesis is one of scale. During the opening phases of early diagenesis the newly buried sediments remain in contact with their original environment of deposition by means of circulating pore waters, and it is not until direct contact is broken that modifications of mineralogy and texture begin to occur. Even so these modifications mainly involve the redistribution of components already present within the ores rather than the introduction of material from outside. However, after cementation an ironstone is so far removed from its original environment that the primary minerals often become unstable, and are readily replaced by the increasing number of mineral ions being introduced from outside the ore bed. Thus a completely different suite of minerals make their appearance during late diagenesis, having little relationship to the original mineralogy.

B. THE PARAGENETIC SEQUENCE

The paragenetic sequence given in figure 38 is based on the conclusions drawn during the foregoing sections. At times the relationships between different minerals have been fixed directly, as for example where an early void filling is euhedral to a later filling or where a late spar is observed to replace an earlier one, but in some instances it is only possible to infer a relationship indirectly. The three effects listed in column (i) of figure 38 (burrowing, spastolithisation, and solution-collapse) are particularly useful in this respect. For example the replacement of ooliths inhibits spastolithisation and thus

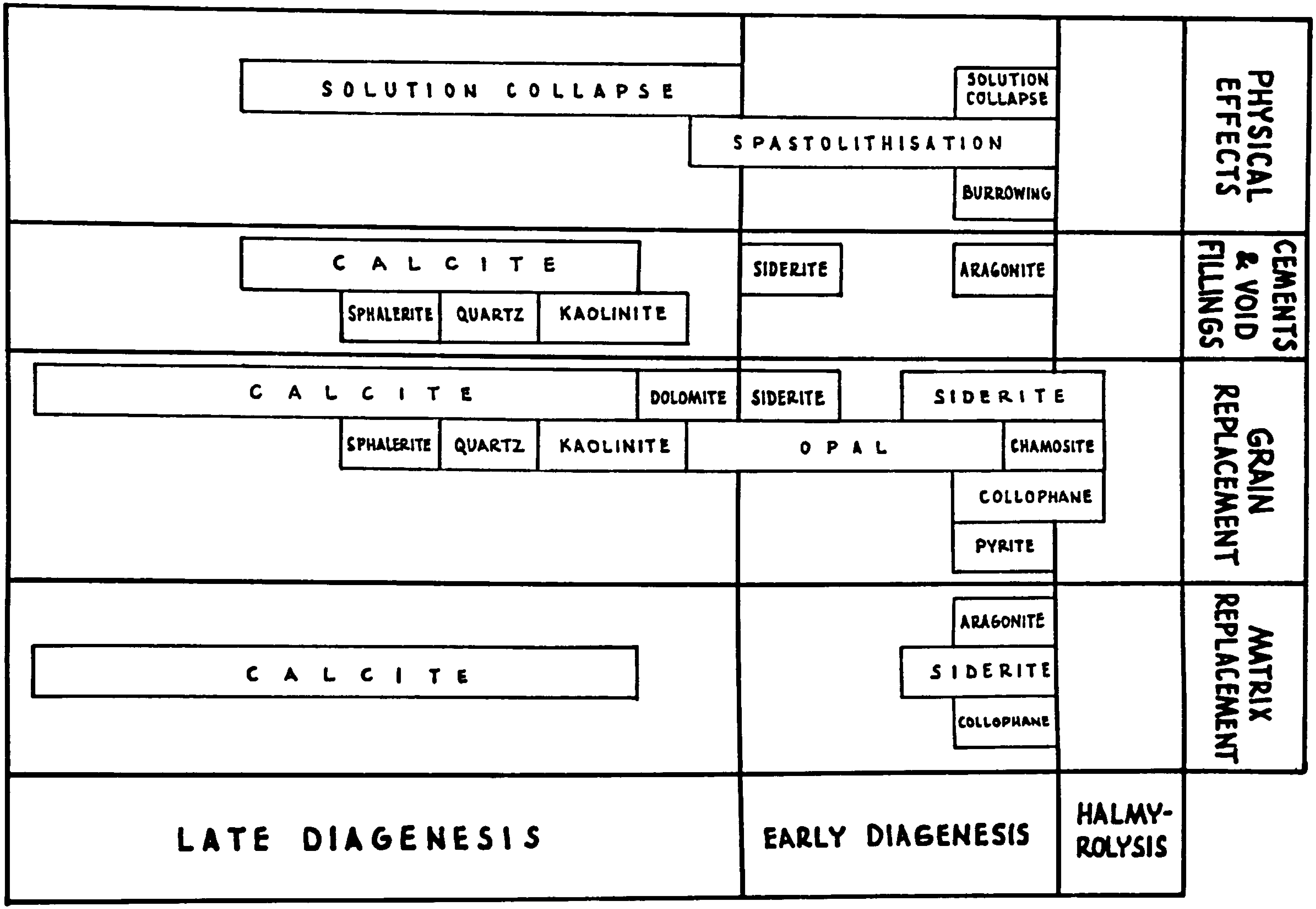


FIG. 38. PARAGENESIS.

replaced spastoliths are usually regarded as late diagenetic in origin. Where void fillings are concerned the spars which fill primary voids are always considered to precede those in secondary voids unless the same mineral occurs in both in which case the fillings are judged contemporary. It is always assumed that no two minerals which share metal ions or carbonate radicals will form simultaneously at the same locality although they may form contemporaneously at different localities.

C. HALMYROLYSIS (Hummel 1922)

At the sediment-water interface the processes of deposition and diagenesis meet and overlap. In a completely open system minerals both above and below the interface attempt to reach equilibrium by a constant exchange of ions. The process is exactly akin to terrestrial weathering and has been called submarine weathering or halmyrolysis (Hummel 1922, p. 41). Like terrestrial weathering it is both destructive and constructive at the same time. Some minerals undergo solution and replacement, others are precipitated or form as pseudomorphs. However, while the process of replacement is usually easily recognised the effects of solution are much more difficult to determine and the reprecipitated minerals are indistinguishable from minerals precipitated directly from sea water.

In the Cleveland Ironstones the most important halmyrolytic replacement mineral is collophane where it occurs in the intraclasts, but chamosite, siderite and possibly pyrite also develop either on the sea floor or in superficial sediments which are subject to reworking.

That solution takes place appears to be indicated by the extraordinarily low percentage of terriginous material which occurs in the ironstone facies and particularly in the chamositic facies (see also pages 315-317). It is postulated that the destruction of clay minerals originally coated with iron oxide during prolonged conditions of submarine weathering, could have provided sufficient iron, silica and alumina to lead to the formation of chamosite as a primary halmyrolytic mineral both in the ooliths and the matrix. This appears to be precisely the process by which chamosite pellets are forming at the present day in the Niger and Orinoco Deltas (Porrenga 1965, 1966, 1967) although the degree of water agitation is insufficient for the formation of ooliths.

The mechanism of iron enrichment is probably similar to that in laterites where it is the preferential solution of silica and alumina under conditions of tropical weathering, which leads to the concentration of iron. In this respect it is interesting to note that the only occurrence of chamosite outside the sedimentary iron ores and associated sediments is in the bauxitic clays of Ayrshire (Wilson 1922) and the lateritic lithomarges of Co. Antrim Ireland (Dunham and Eyles in Brindley 1951a, p. 522-524). Significantly all these chamosites are believed to have formed by the lateritic weathering of basalts. Brindley (op.cit.) has shown that although the Ayrshire material contains a higher percentage of alumina than is usual in ironstone chamosites the minerals are almost identical.

D. EARLY DIAGENESIS

During early diagenesis the process of iron enrichment, which began during halmyrolysis, was continued by the introduction of siderite into the ironstones, initially as a replacement spar and later as a cement. The importance of this mineral cannot be overstressed since on the basis of Taylor's work (1949, p. 48) it probably contains approximately 40 percent of iron compared with a little over 30 percent in chamosite.

Although siderite replacement may have commenced in some ooliths on the sea floor, it was within the matrix after burial, that this process was most important. Siderite microsparites occur in all the seams, principally within the wackestone and mudstone facies, as a result of the replacement of chamosite together with detrital clay minerals and quartz. Alongside pyrite and collophane the mineral also occurs as a replacement of the chamosite ooliths, especially in the packstone facies, possibly releasing opaline silica as a by-product.

The earliest cement to be introduced was aragonite which occurs patchily in the Main, Two Foot, Raisdale and *Avicula* Seams probably following the solution of aragonite shells elsewhere in the same beds. The presence of aragonite is taken to indicate high salinities possibly arising through evaporation at times when the oolite shoals were exposed.

The phase of early diagenesis is considered to be terminated by the deposition of the siderite cements, where they occur in the grain rich facies of the Main, Two Foot and Raisdale Seams. In each of these seams a considerable degree of compaction had been effected by means of spastolithisation by the time cementation took place, but precisely how much overburden was present is impossible to say. Apparently the Main Seam remained uncemented at the time of the Upper Lias transgression for the siderite spars at the top of the Seam are without trace of pyrite replacement. Presumably the nature of the 'Sulphur Band' would have been quite different had cementation occurred; there would have been abundant intraclasts but very few loose ooliths. If the cementation of the Main Seam took place at some time during the *tenuicostatum* zone therefore, it is possible that the *margaritatus* ironstones were cemented during the *spinatum* zone. However, the evidence remains very tenuous.

E. LATE DIAGENESIS

Following the precipitation of the siderite cements no further iron minerals were introduced and therefore late diagenesis represents a period of deterioration in the ores. New minerals such as calcite, dolomite, quartz, sphalerite and kaolinite were probably introduced from outside the ironstone seams rather than from within. They developed both void filling and replacement spars in most cases; spars which are indistinguishable in the absence of relict textures or solution collapse phenomena.

Of these spars dolomite is mainly restricted to the Two Foot Seam in the Blackmoor area, and quartz only occurs in the grain rich facies of the Main Seam. Kaolinite occurs in all the seams but has a particular affinity for mudstone and wackestone facies. Sphalerite occurs in various facies in the Main, Pecten, Two Foot, Raisdale and Avicula Seams. The most pervading of all spars is calcite which occurs as a late cement, a void filling, and as a replacement of ooliths, matrices and to a certain extent of earlier spars as well. There were undoubtedly several generations of calcite in each seam probably extending over long periods of time but precisely how many is not known.

VIII F A C I E S

A. MAIN SEAM

As described on page 59 the Main Seam may be divided into four units as follows:-

(iv) Top Block

(iii) Middle Band

(ii) Bottom Block

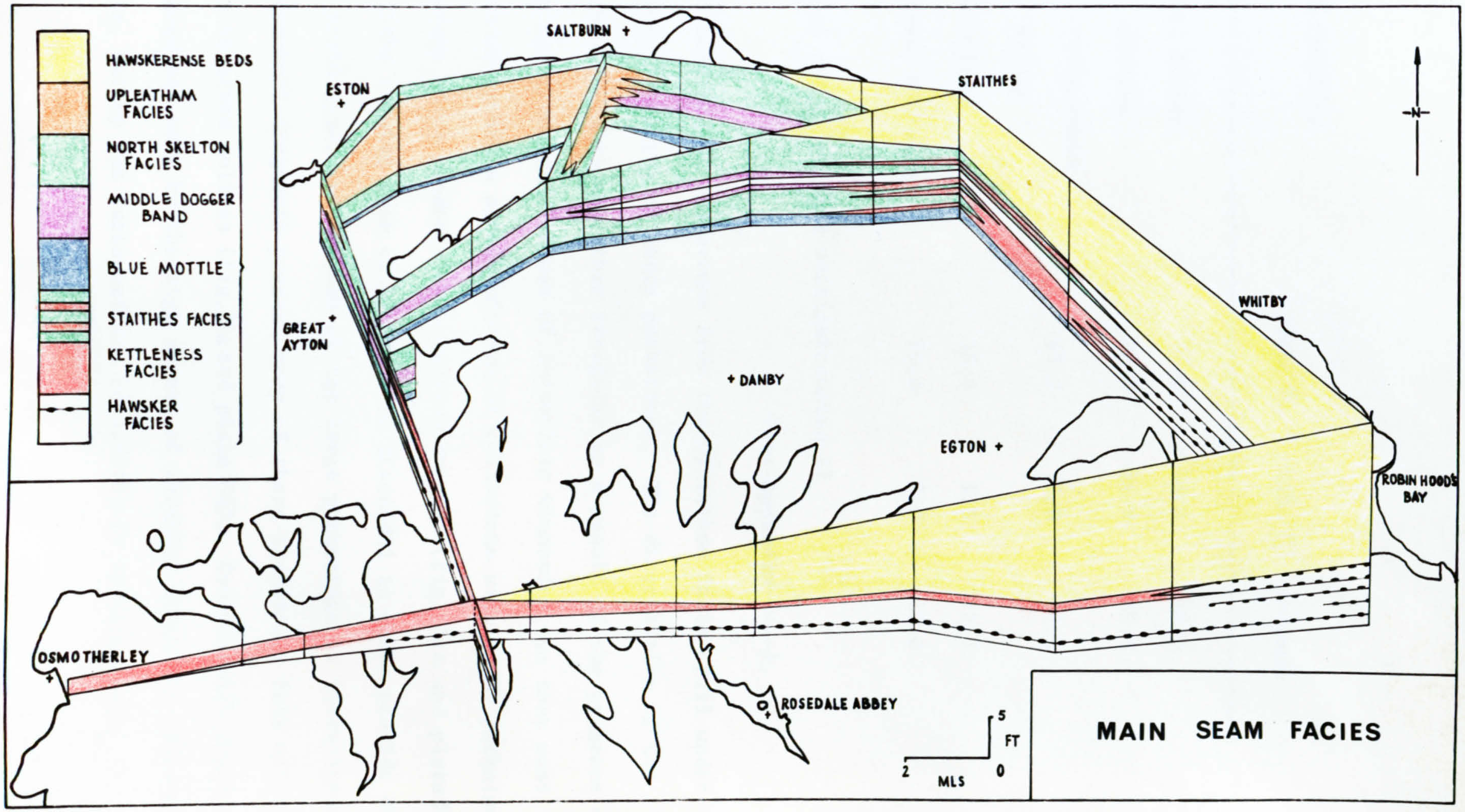
(i) Blue Mottle

The correlations in figure 18 are made on the assumption that the divisions between these units may be regarded as isochronous but the situation is complicated considerably by the diachronous nature of the ironstone facies illustrated diagrammatically in figures 19 and 39.

1. The Upleatham Facies

The approximate areal extent of the Upleatham facies is illustrated in figures 21 and 39 . Of all the facies it is the most diachronous cutting right across the Middle Band, so that the seam lacks its usual division and was worked as a single block. Judging by the compilation of analyses given by Hatch (1918, p. 105) mines in which the Upleatham facies was well developed gave ores averaging 30.2 percent iron in the raw stone, higher than any other facies.

FIG. 39.


HAWSKERENSE BEDS
UPLEATHAM FACIES
NORTH SKELTON FACIES
MIDDLE DOGGER BAND
BLUE MOTTLE
STAITHES FACIES
KETTLENESS FACIES
HAWSKER FACIES
SALTBURN
ESTON
STAITHES
N
WHITBY
GREAT AYTON
DANBY
EGTON
ROBIN HOOD'S BAY
OSMOTHERLEY
ROSEDALE ABBEY
5
FT
2
MLS
0
MAIN SEAM FACIES

a) <u>Modal Analyses</u>

	max. %	min. %	average
Total grains	77.0	48.5	66.3
Ooliths	60.8	16.8	46.8
Intraclasts Shells	55.2	2.0	19.5
Mud matrix	32.2	1.5	21.7
Primary porosity	24.0	3.2	12.0

Total number of thin sections counted 17

~~(see Appendix ——)~~.

The majority of ironstones from the Upleatham facies fall under the category of sparry or muddy packstones. The distribution of the muddy matrix tends to be rather irregular as a result of the presence of burrowing organisms and because of incomplete winnowing, so that most thin sections reveal a patchy mixture of grainstone with muddy packstone or wackestone which produces the observed average (fig. 34a and plate 32a).

Ooliths ranging from ellipsoidal to discoidal in shape provide the dominant grain type, but because of the large percentage of intraclasts and rounded shell fragments present many of these ironstones fall within the class of mixed oolites (fig. 36a and plate 32b). Considerable reworking is indicated not only by the high degree of abrasion among the intraclasts and shells, but by the juxtaposition of ooliths in various stages of

PLATE 30 Main Seam 1' - 5' from top.

Columnar section.

North Skelton Mine

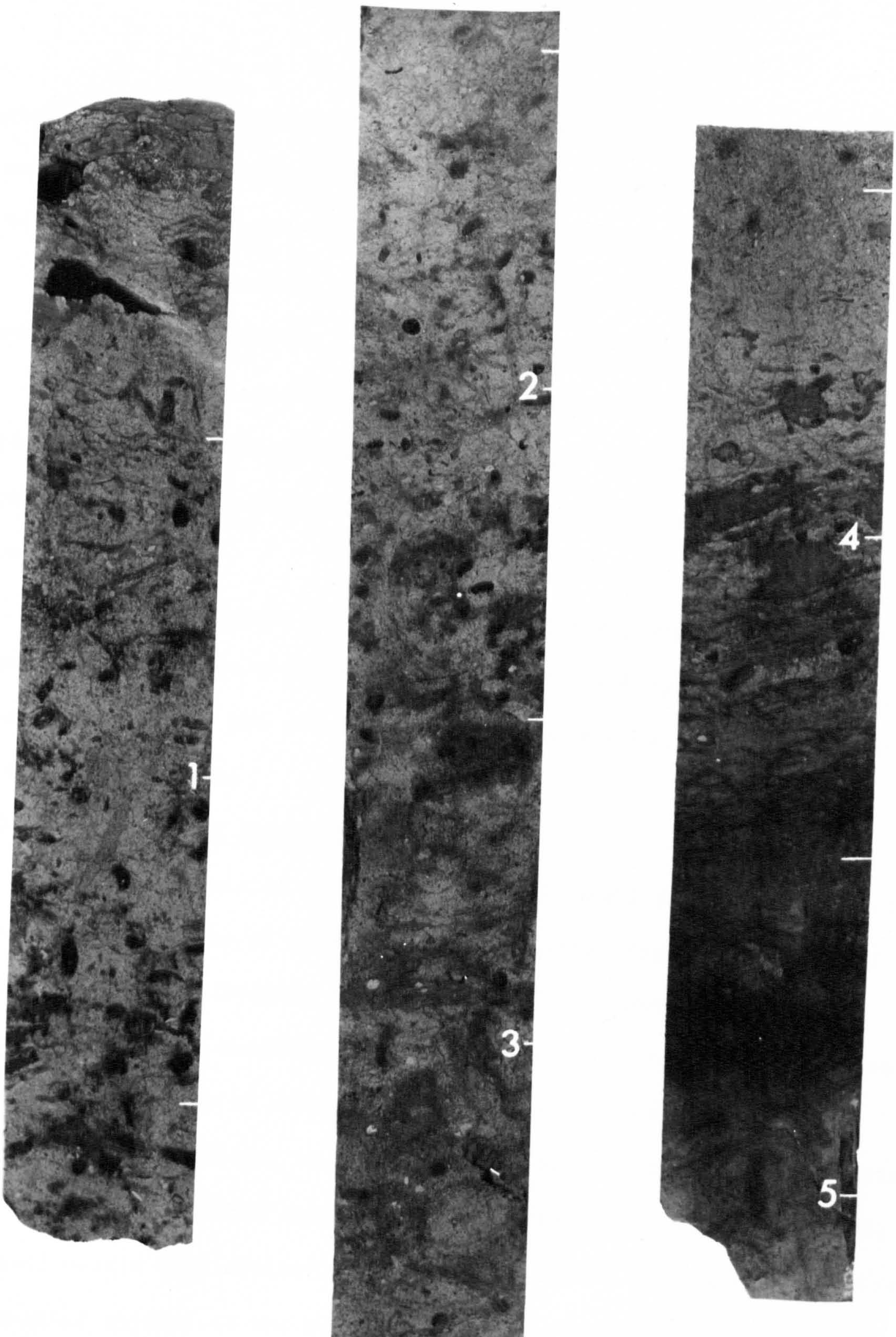


PLATE 30

replacement by halmyrolytic siderite. Among the normal ooliths a small percentage of foliaceous ooliths were recognised and are taken to indicate algal activity within the sediment.

Some rocks contain a trace of terriginous quartz grains of fine sand size, but these are always replaced by siderite during diagenesis.

One of the most distinctive characteristics of this facies is the presence of a bright green chamosite mud contaminated by a small percentage of diagenetic siderite, but otherwise completely free of impurities.

The total amount of original chamosite represented by the ooliths and matrix averages a little under 70%, of which approximately 35% remains following the sideritisation of the grains, and, to a lesser extent, the matrix.

b) Environment of Deposition

The importance of intraclasts, rolled shell fragments, and ooliths in different stages of replacement by siderite, together with local evidence of cross-bedding indicates that the Upleatham facies was accumulated under conditions of high energy, probably by the erosion and redistribution of neighbouring ironstone facies. There is no evidence of channelling or erosion either beneath the Upleatham facies or in the beds further south, so that the facies probably represents a fossil oolite bank derived by the redistribution of ironstones previously deposited further to the north, beyond the present outcrops.

PLATE 31 Main Seam 5' - 9'6" from top.

Columnar Section.

(For key see figure 18)

North Skelton Mine

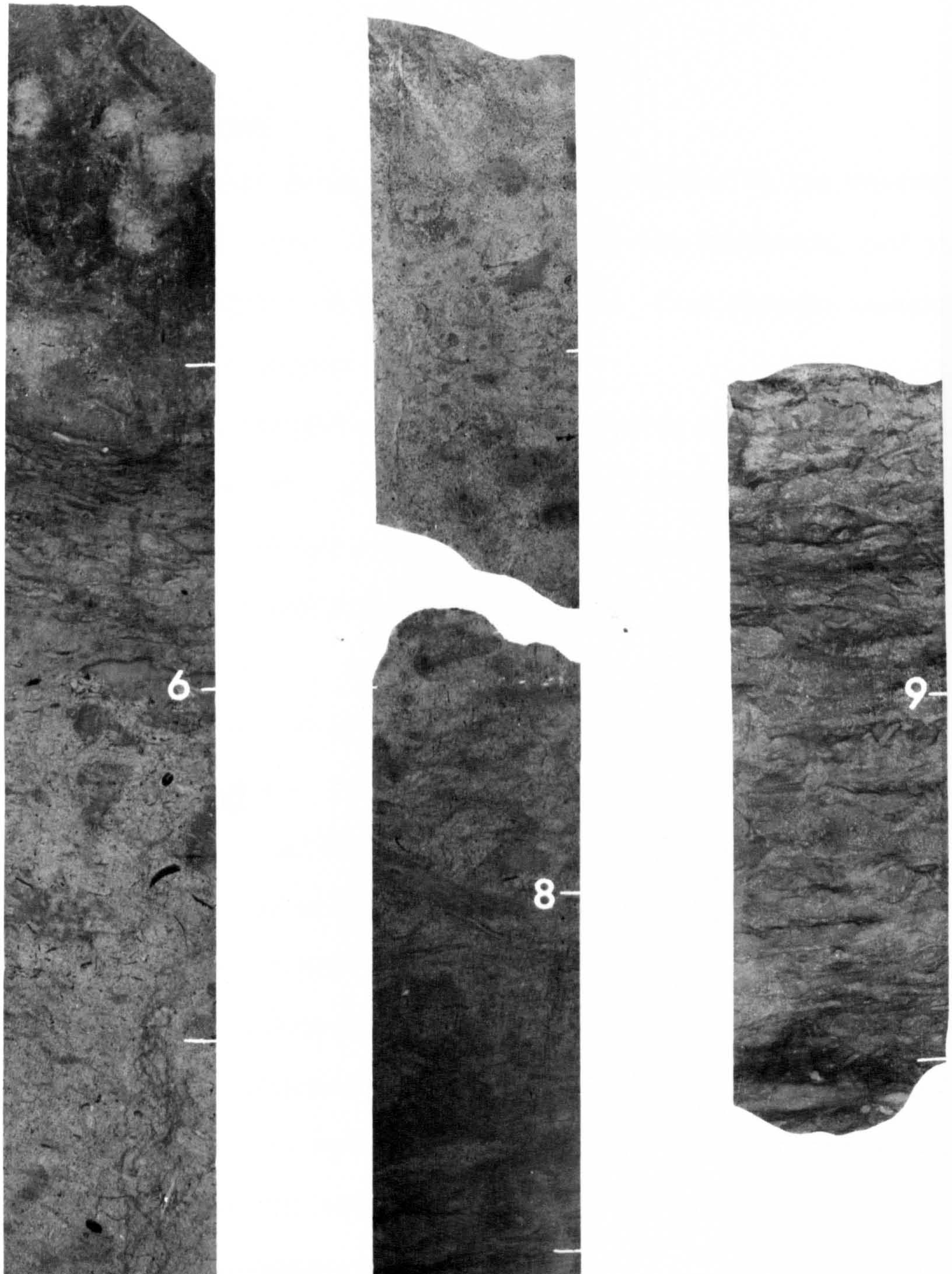


PLATE 31

PLATE 31 Main Seam 5' - 9'6" from top.

Columnar Section.

(For key see figure 18)

North Skelton Mine

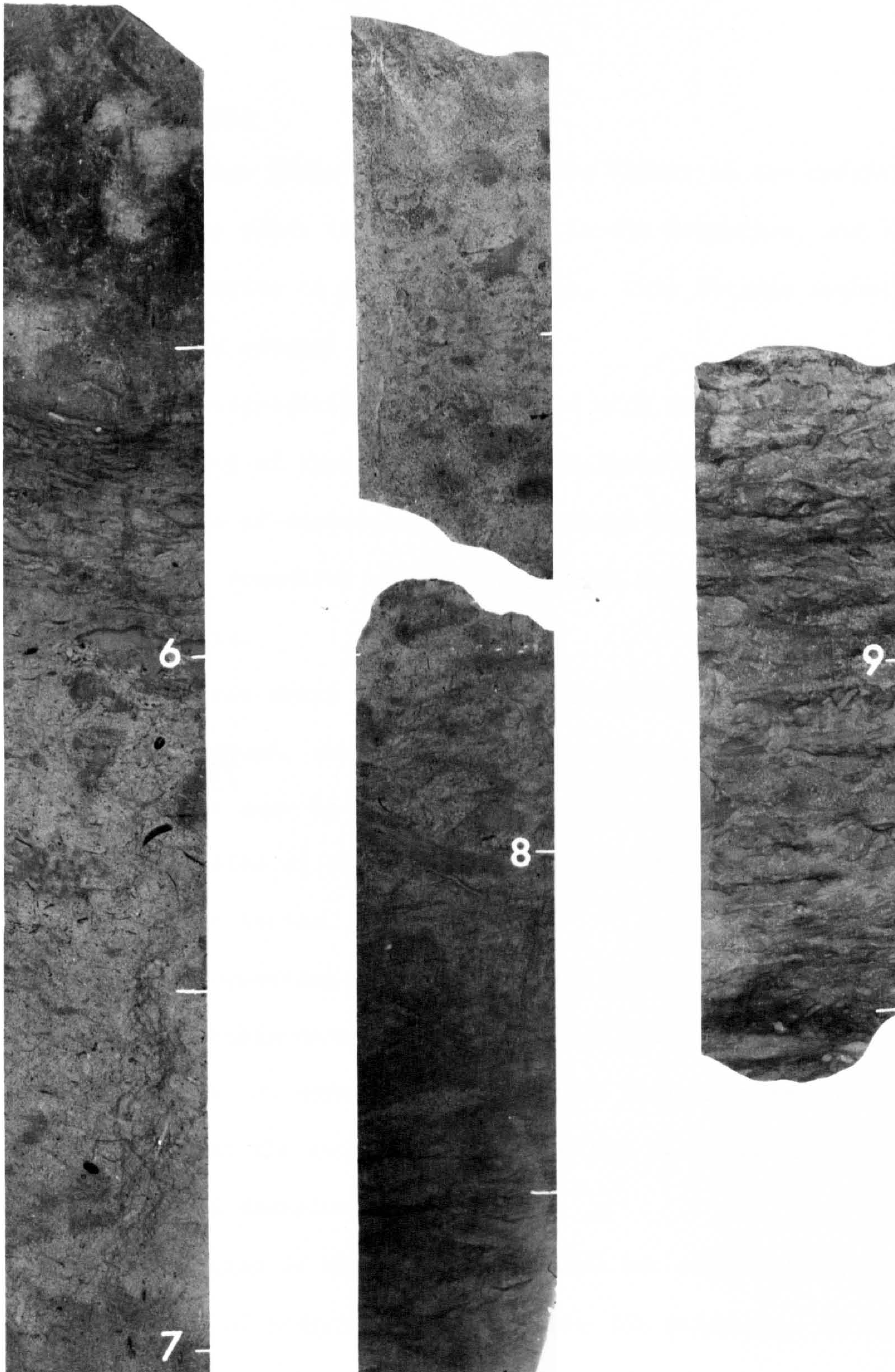


PLATE 31

c) Early Diagenesis

The percentage grain sideritisation is higher in the Upleatham facies than in any other ironstone facies in the Formation, and the percentage of siderite in the matrix is low. This strange anomaly probably arises in several ways:-

(i) The juxtaposition of sideritised with unsideritisedooliths indicates that many of these grains were replaced before they reached their present site of deposition either through halmyrolytic replacement or because of the reworking of sediments which had already been subject to early diagenesis.

(ii) In cases where the relative sideritisation of all the grains is approximately equal, that is where replacement appears to have taken place 'in situ' it must be assumed that some thermochemical difference between the chamosite of the matrix and ooliths favoured the preferential replacement of the latter.

(iii) By comparison with the siderite rinds of the North Skelton facies the grain replacement in the Upleatham facies is often highly ly irregular and does not appear to give rise to opal as a by-product, which suggests that the mode of emplacement was slightly different from that normal in the packstones.

The cementation of the Upleatham facies was effected entirely by the precipitation of siderite, and therefore the percentage of this mineral cement coincides exactly with the percentage of primary porosity.

PLATE 32 Upleatham Facies, Main Seam

a) Mixed oolite, Skelton Beck
5'3" from top. Note burrow.

b) Intraclastic ironstone.
Skelton Beck. 2' from top. x 10

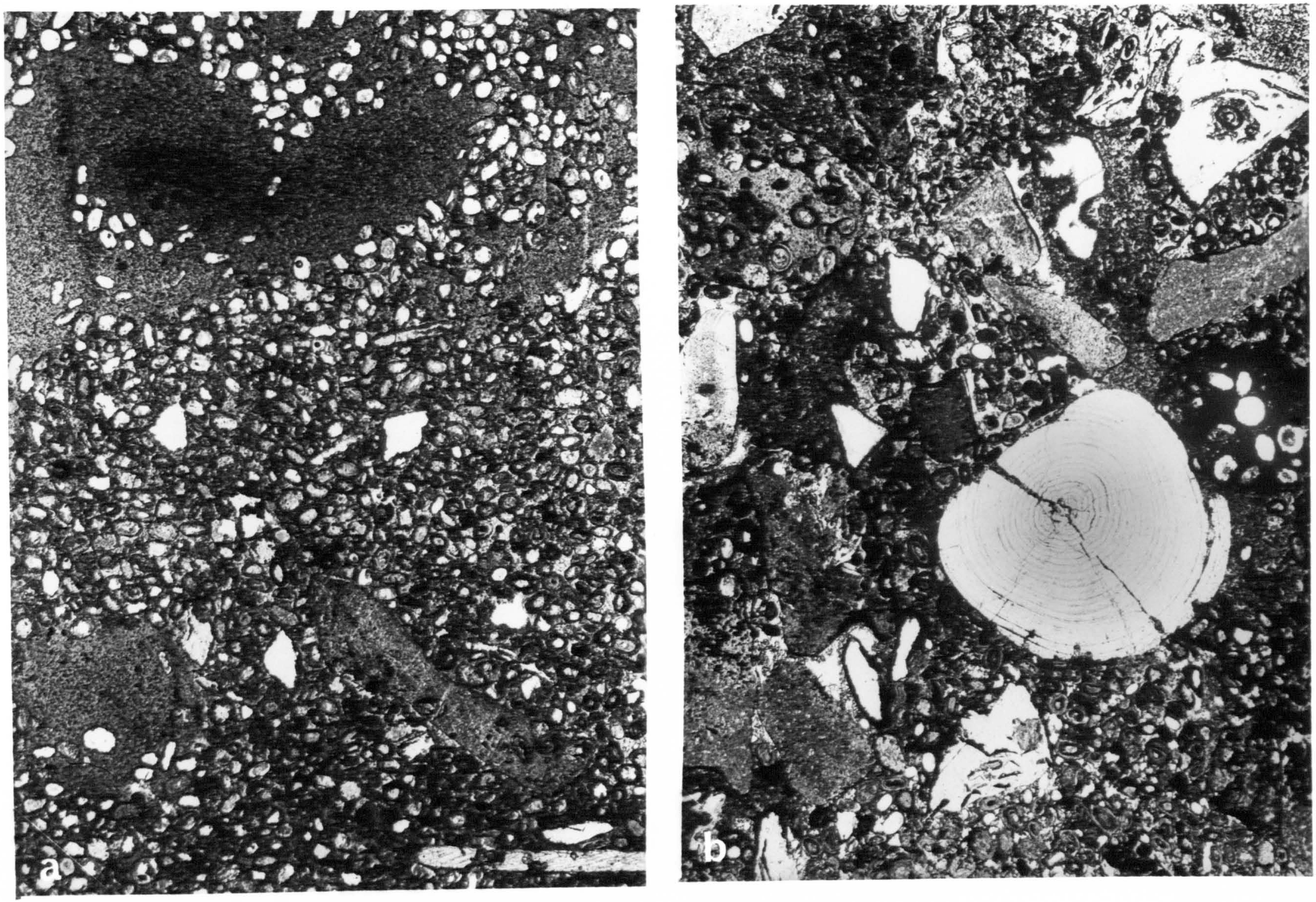


PLATE 32

Given an average porosity of 12 percent and a figure of about 30 percent for the amount of siderite introduced into the grains, the total percentage of early diagenetic siderite must be around 45-50 percent, allowing for a small amount of siderite in the matrix.

d) Late diagenesis

The only modifications to take place in this facies during late diagenesis were the introduction of small percentages of calcite, sphalerite and quartz as void fillings, following the solution of unstable aragonite shells and some intraclasts. No replacement spars of this age occur.

e) Conclusion

On the basis of modal analyses the average amount of chamosite in the Upleatham facies is calculated as approximately 35 percent, the amount of siderite as 47 percent equivalent to approximately 39 percent $FeCO_3$ given that the siderite contains 83 percent $FeCO_3$ (Taylor 1949, p. 48). This compares favourably with the mineral composition of Eston ironstone, calculated by Hallimond (1925, p. 51) from Stead's chemical analysis (1910), as chamosite 34.24 percent, $FeCO_3$ 34.70 percent. However, the modal analyses indicate an iron content of approximately 29.2 percent a little lower than the figure of 31-33 percent in stone dried at 212^{o}F given by Anderson (in Whitehead et al. 1952, p. 43).

2. The North Skelton facies

South of a line drawn from Brotton in the east to Guisborough in the west (fig. 21) the Main Seam is split into two blocks by the development of the Middle Band and the Upleatham facies gives place to the North Skelton facies, the percentage of iron in the raw stone declining to around 28.2 percent according to Hatch (loc. cit.).

a) Modal Analyses

	max. %	min. %	average
Total grains	65.8	54.0	60.2
Ooliths	62.2	32.0	55.4
Intraclasts	13.8	0.4	4.2
Shells	4.0	0	0.6
Mud Matrix	40.2	12.4	30.9
Primary porosity	21.8	3.4	8.9

North Skelton facies, Top Block, (thin sections 17)

	max. %	min. %	average
Total grains	71.6	32.0	54.9
Ooliths	70.2	32.0	52.8
Intraclasts	6.6	0	1.8
Shells	1.0	0	0.3
Mud Matrix	67.6	9.4	33.8
Primary porosity	26.2	0.4	10.3

North Skelton facies, Bottom Block, (thin sections 10)

PLATE 33 North Skelton facies, Main Seam

a) High oolite packstone, Skelton Beck. 1'0" from top.

b) Sparry oolite packstone. Top Block, North Skelton.

x 10

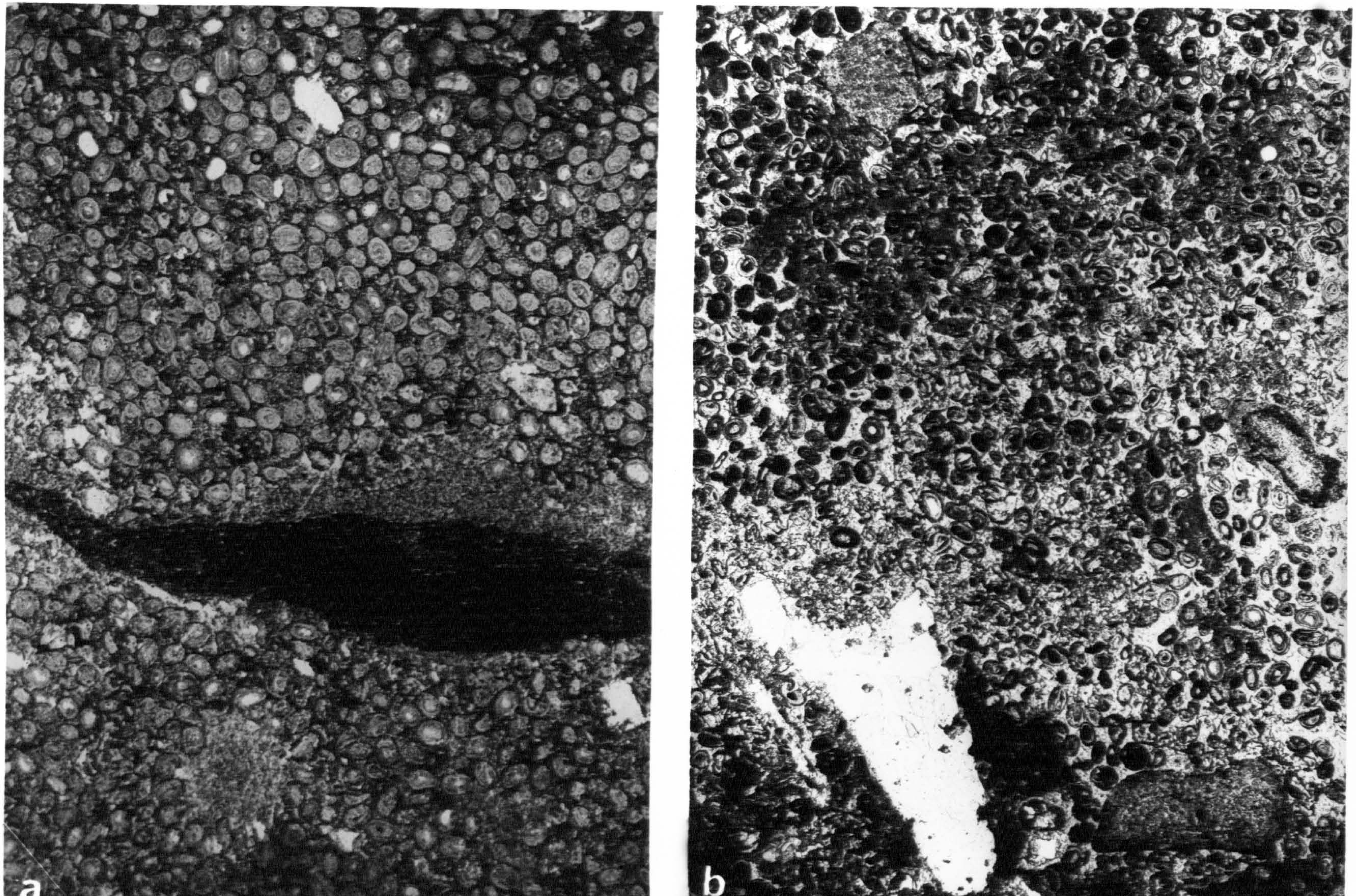


PLATE 33

By comparison with the Upleatham facies the North Skelton facies contains a higher percentage of mud matrix and a lower grain total although the overall percentage of ooliths is increased. With respect to the distribution of grains and matrix this facies shows even more variation than the former, as the result of the interburrowing of mudstone with grainstone (plates 30,31 and 33,34). As far as possible burrows were avoided during modal analyses; on this basis the average rock from this facies is a muddy packstone, but when the burrows are taken into account the average falls to just within the wackestone facies (fig. 34a).

The Top and Bottom Blocks of the Seam in the North Skelton facies are similar in many respects although the ratio of matrix to grains is increased in the latter. This reflects the tendency for the Bottom Block to deteriorate somewhat more rapidly than the Top. (plates 33 and 34).

On the basis of the relative percentages of ooliths, intraclasts, and shells sediments from this facies may be classed as high oolite deposits (fig. 36a). However, it must be pointed out that the relatively high percentage of mud indicates the existence of a large amount of faecal material, partly in pellet form, for which no account is taken. Ooliths are mainly ellipsoidal rather than discoidal and slightly larger in the Top Block (mean size 0.6 mm.) than in the Bottom (mean size 0.5 mm.).

Unlike the matrix of the Upleatham facies the chamosite muds of the North Skelton facies are pale olive grey in thin section, partly as a result of contamination by diagenetic siderite but possibly because

PLATE 34

a) Spastolithic chamosite oolite and sideritic shale. Middle Band, North Skelton.

b) Muddy oolite packstone. Bottom Block, North Skelton.

x10

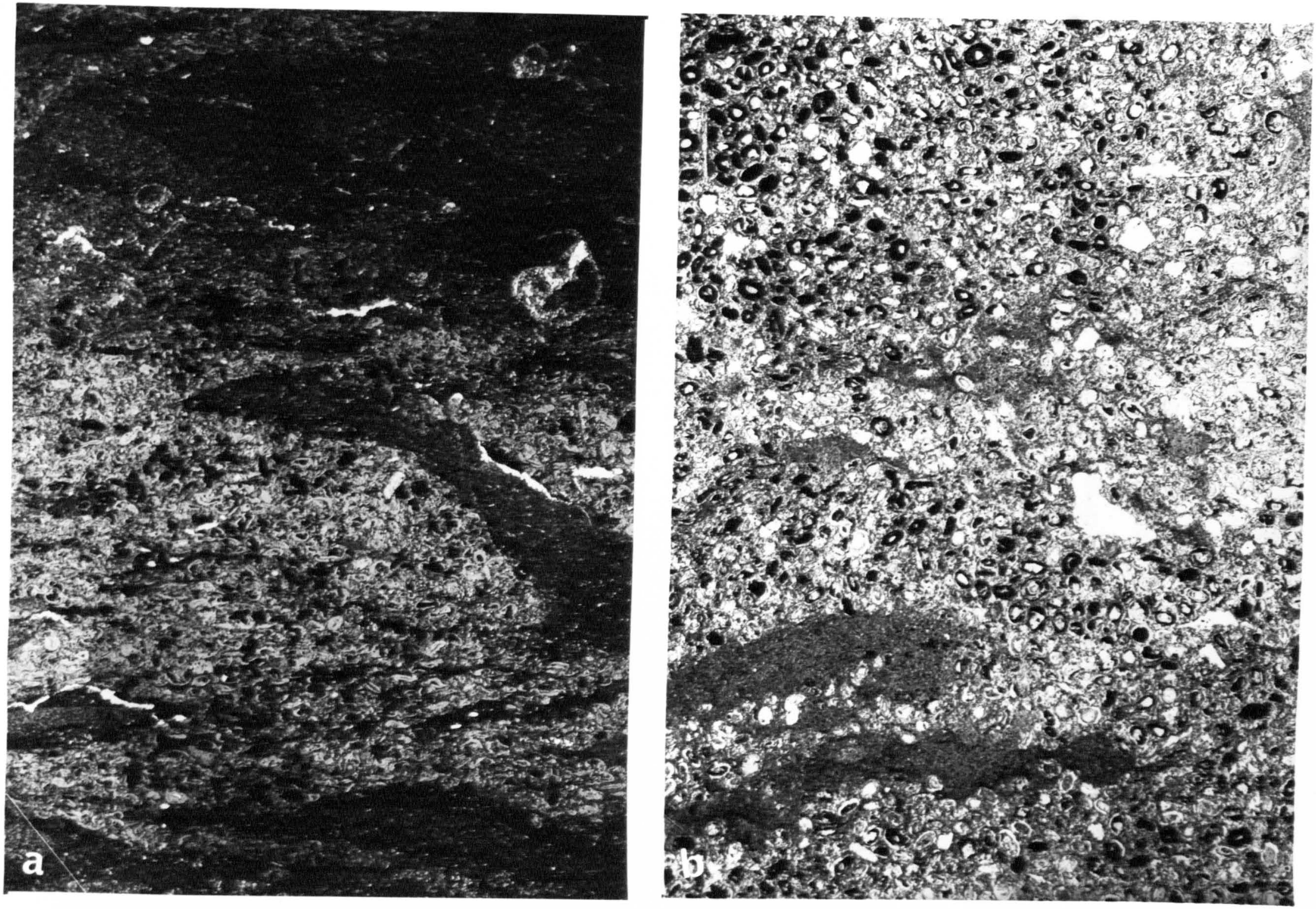


PLATE 34

of a low iron content in the chamosite, or perhaps as a result of an admixture of terriginous clay minerals. Modal analyses revealed only a trace of fine sand sized terriginous grains, however.

b) The Middle Dogger Band

Throughout the majority of the area occupied by the North Skelton facies the Middle Band was worked along with the Top and Bottom Blocks of the Seam (see fig. 21). It comprises two parts (see page 63), an upper layer consisting of intercalations of spastolithic oolite, extensively interburrowed with chamosite-siderite mudstone and terriginous shale (plate 34d), overlying a layer of siderite mudstone.

Modal analyses give the following averages:-

	upper layer	lower layer
Total grains	25.0	6.0
Ooliths	24.3	6.0
Intraclasts	0.3	0
Shells	0.4	0
Mud Matrix	69.4	94.0
Primary porosity	5.6	0

At the southern limits of the North Skelton facies (see fig. 21) the upper layer of the Middle Band passes into a shale, which necessitated the Seam being worked in two separate parts; the lower siderite mudstone layer persists, however.

c) The Blue Mottle

The transition between the Bottom Block and the Black Hard Shale is made by a rock referred to in this work as the 'Blue Mottle' owing to the abundance of the trace fossil Rhizocorallium (page 66) The rock is a sideritic-chamosite mudstone containing occasional spastolithic ooliths (plate 36a). It maintains much the same appearance throughout the northern orefield, although it is more chamositic and contains a higher proportion of spastoliths in the northerly group of mines.

d) Environment of Deposition

The North Skelton facies of the Main Seam lacks the evidence of high energy conditions shown by the Upleatham facies; there are fewer intraclasts, and shells where they occur are broken but unrounded; evidence of current bedding is totally lacking. The abundance of ooliths in the Top and Bottom Blocks suggests that these beds represent fossil oolite shoals accumulated 'in situ' with very little reworking and redistribution. The percentage of mud is higher than might be expected by comparison with recent aragonite oolite shoals (page 268) but this arises mainly as a result of the activity of burrowing organisms after deposition. It is also suggestive of quieter water conditions than those to which we are accustomed for the formation of ooliths.

Both the Top and Bottom Blocks undoubtedly accumulated under shallow water conditions, although there is no evidence of emergence having taken place. According to Farrow (1966) the occurrence of

Rhizocorallium in the 'Blue Mottle' and to a lesser extent in other parts of the seam may be taken to indicate a shallow sub-littoral environment of deposition. The intercalation of the Middle Dogger Band brings the North Skelton facies into juxtaposition with ironstone types found more commonly further south in the Staithes facies and therefore appears to indicate the regression of the oolite shoals probably resulting from an increase in water depth following slight subsidence.

e) Early diagenesis

Like the Upleatham facies the North Skelton facies underwent a high degree of sideritisation during early diagenesis, but in this case not only in the grains but the matrix also. Modal analyses suggest an average grain sideritisation of about 35 percent, matched by a similar percentage in the matrix. Grain sideritisation was particularly favoured in the muddy packstone and wackestone lenses where distinctive siderite rinds are developed on the ooliths, intraclasts and aragonitic shells. The overall uniformity of these rinds suggests that they were formed within the sediment by the carbonation of chamosite, a process which appears to have resulted in the release of opaline silica from the ooliths.

The carbonation of the matrix dates from the same time, but whereas the grains develop finely mesocrystalline pseudospars the former develops random xenotopic microspar crystals characteristically with cloudy cores resulting from the presence of inclusions.

Spastolithisation is a widespread phenomenon, especially within the top six inches of the Top and Bottom Blocks. At both these horizons sparry packstones with grainstone lenses predominate. As elsewhere in the facies this rock type unsupported by a mud matrix and usually without the strength given to the grains by sideritisation, is particularly liable to compaction.

Once again as in the previous facies the primary porosity was occluded almost entirely by siderite although calcite may occur as a late filling in some large open burrows.

f) Late diagenesis

Following a certain amount of solution collapse, calcite, quartz and sphalerite were introduced as late void fillings in Top and Bottom Blocks and also occur as replacement spars. However the total figure for these spars rarely rises above 1-2 percent in any rock. The tendency for these void fillers to occur in the vicinity of large burrows suggests that acid solutions capable of dissolving chamosite were derived from the source during late diagenesis.

The only other replacement spar to occur is kaolinite, but this mineral only assumes real importance in the Staithes facies.

g) Conclusions

Modal analyses indicate a clay mineral content of approximately 57 percent taking the ooliths and matrix together, yielding approximately 17 percent of iron if the clay mineral is assumed to be pure chamosite. The total percentage of siderite resulting from replacement in the grains and matrix and from void filling averages 39 percent of which approximately

32 percent is $FeCO_3$ (Taylor loc. cit.) giving 15.6 percent of iron. The total iron content of the Top and Bottom Blocks is therefore calculated at approximately 32.7 percent, compared with a given value of 28 to 30 percent for stone dried at 212°F (Anderson in Whitehead et al. 1952, p. 43).

The figure calculated for the North Skelton facies exceeds that given for the Upleatham facies and clearly overestimates the tenor of the ore, partly because the Middle Band is excluded and partly because the chamosite is always contaminated by alteration products. After having accounted for siderite, approximately 13.4 percent of iron remains, indicating a chamosite percentage of 40.2. By subtraction from the figure given previously the percentage of non ferruginous contaminant amongst the clay minerals must be about 18 percent.

The top layer of the Middle Dogger Band passing laterally into shale provides a lean ore, but according to Wright (in Stead 1910, p. 36) the lower siderite mudstone "is almost always the richest part of the seam". Hallimond's analysis of 'Dogger Stone' probably from this horizon indicates 13.92 percent chamosite with 52.49 $FeCO_3$ giving a figure of 29.4 percent for iron.

3. <u>The Staithes Facies</u>

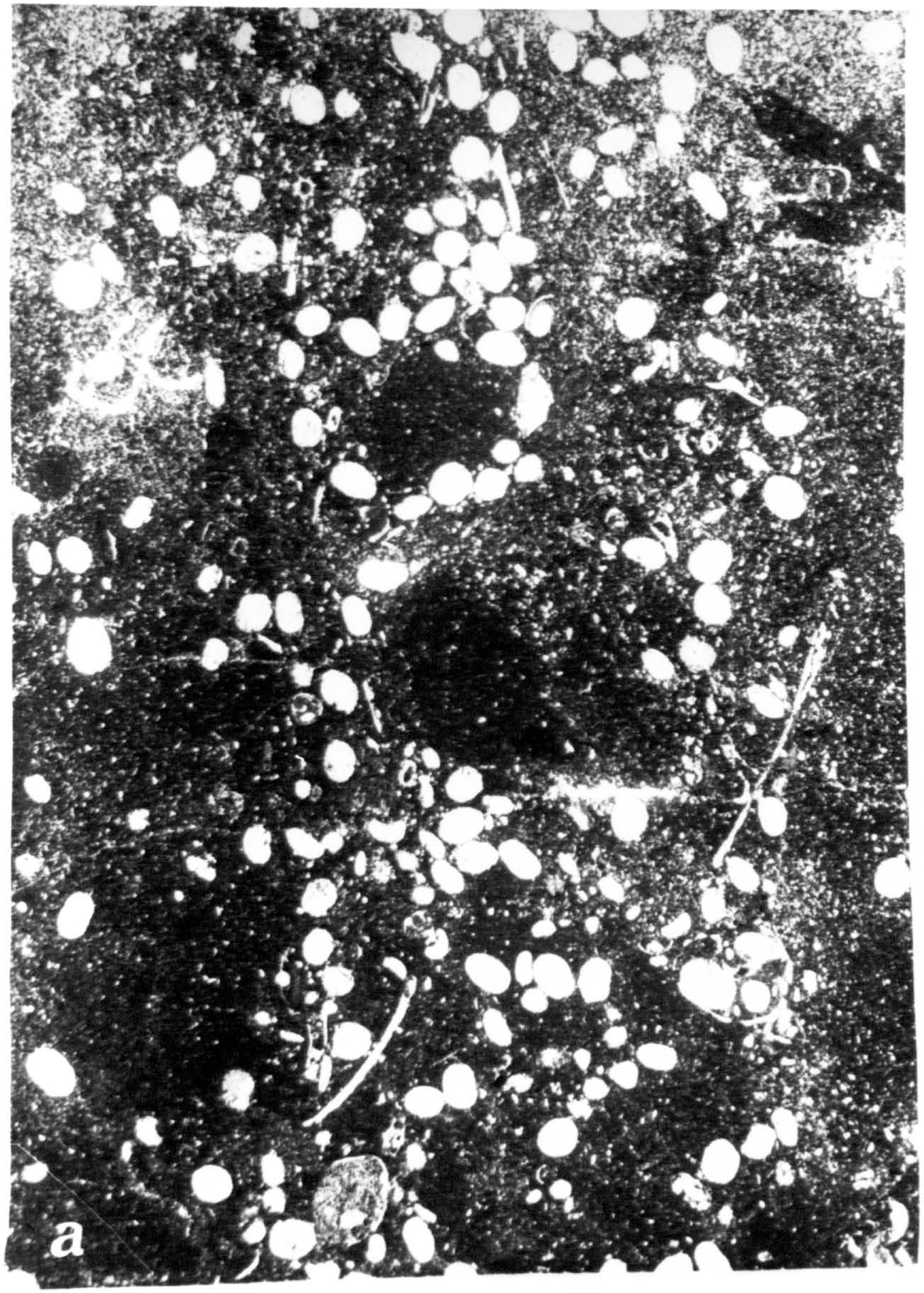
The approximately distribution of the Staithes facies is shown in figure 21 , although for the sake of clarity it is included with the North Skelton facies in figure 39 . The southern boundary of the facies is taken to coincide approximately with the southerly limit of

PLATE 35 Staithes facies, Main Seam

a) Oolitic siderite wackestone. Note effect of burrowing on ooliths.

b) Shelly oolitic siderite wackestone.

x 10



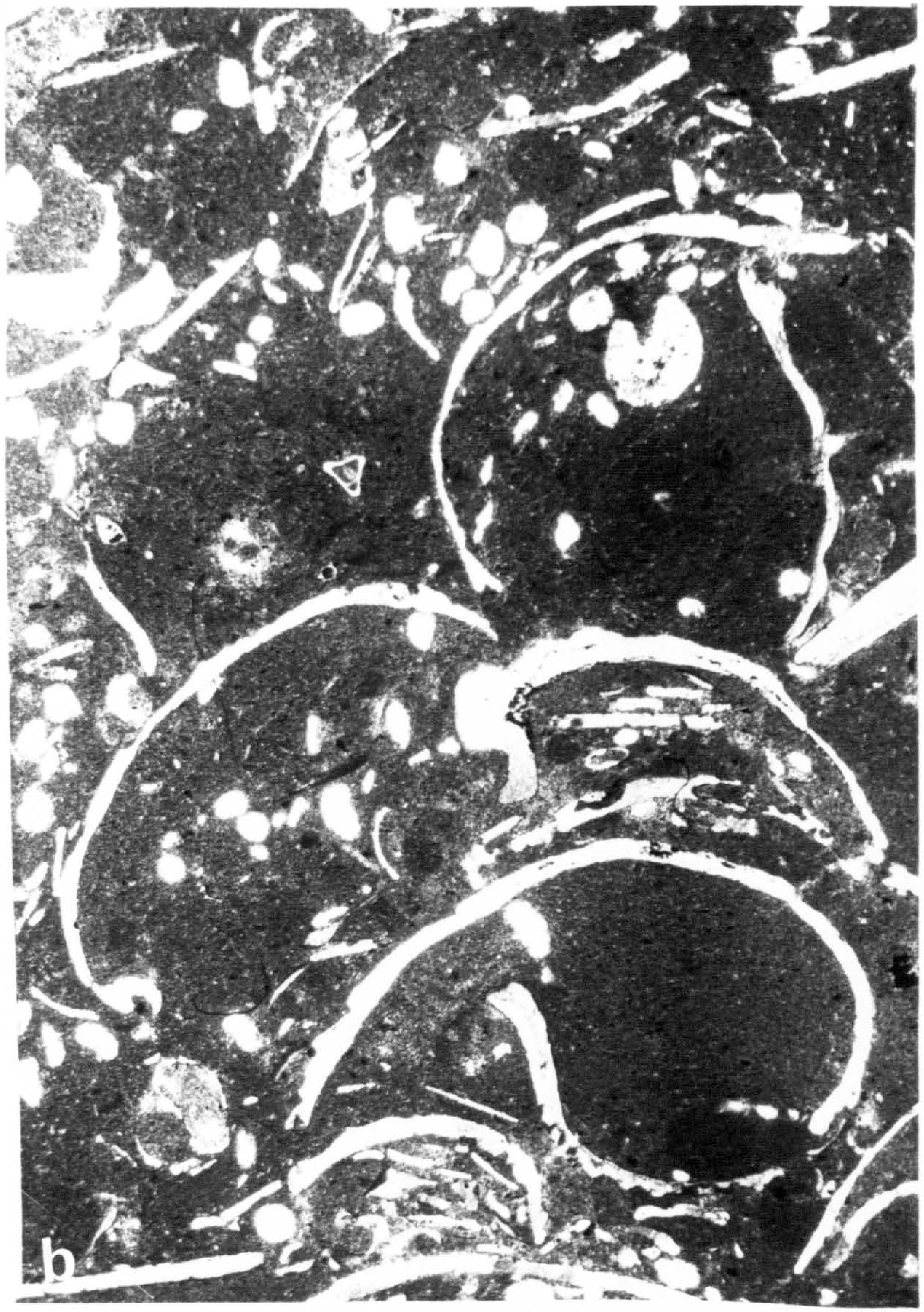


PLATE 35

workable ironstone. Hatch (loc. cit.) gives a figure of 25.3 for the percentage of iron in the raw stone, Anderson (loc. cit.) a figure of 25-27 percent in stone dried at 212^{o}F.

a) Modal Analyses

	max. %	min. %	average
Total grains	48.4	8.5	25.2
Ooliths	46.2	4.5	20.9
Intraclasts	2.0	0	0.7
Shells	15.5	0	3.1
Quartz	3.5	0	0.5
Mud matrix	91.5	43.0	73.1
Primary porosity	9.4	0	1.7

Staithes facies, Top Block (thin sections 12)

	max. %	min. %	average
Total grains	24.0	1.0	7.1
Ooliths	23.0	0	5.9
Intraclasts	3.0	0	0.4
Shells	0.5	0	0.1
Quartz	3.0	0	0.7
Mud matrix	99.0	76.0	92.9
Primary porosity	0	0	0

Staithes facies, Bottom Block (thin sections 9)

Modal analyses of the Staithes facies were carried out from only two localities; the type locality and Whitecliff Mine, by means of the collection of slides held by the Geological Survey. These analyses are therefore a less representative sample of the whole facies than those given previously.

In the Staithes facies the Top and Bottom Blocks of the Seam are split by an increasing thickness of shale, which necessitated that the ore be worked in separate parts in most cases (Barrow 1888, p. 24). The workable parts of the seam comprised an alternation of mudstones and wackestones (fig.34a), in consequence of which the average rock from this facies lies close to the wackestone-mudstone boundary. Both the grain total and the percentage porosity are, therefore, considerably reduced by comparison with the North Skelton facies. The tendency already noted in the latter, for the Bottom Block to deteriorate more rapidly than the Top is even more marked in the Staithes facies, as maybe seen from a comparison of the modal analyses given.

Ooliths are still the dominant grain type, although shells may predominate in some lenses (plate 35b). Of the shells, approximately 72 percent belong to aragonitic species, the remainder being calcite. A large proportion are unbroken although usually disarticulated.

The facies is riddled with burrows of various types (plate 35a) so that the percentage of faecal material is probably higher than in either of the previous facies. Pellets are evident in places but the majority of this material is distributed in the matrix, and quite indistinguishable.

PLATE 36

a) Black Hard Chamositic sideritic mudstone. North Skelton.

b) Siderite mudstone showing septarian cracking due to differential siderite growth. Cracks filled with kaolinite. Staithes.

x 10

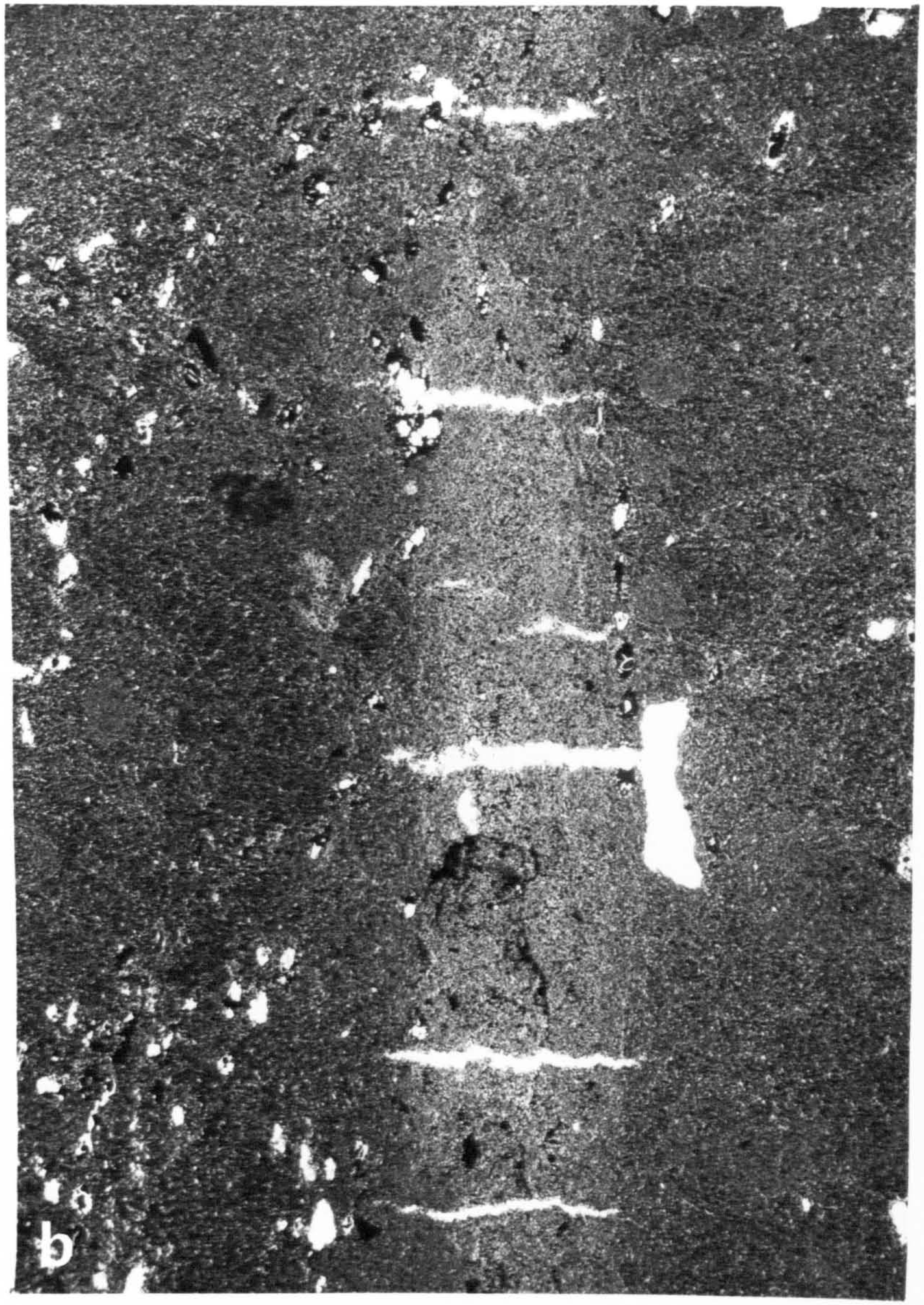


PLATE 36

The overall percentage of mud matrix runs between 43 percent and 99 percent but averages 83 percent, most of which presumably consisted of chamosite originally, although with a small amount of terriginous material signified by the small percentage of very fine quartz sand which occurs.

b) Middle Shale Band

This averages 1-2 ft. thick in the Staithes facies and consists of cryptocrystalline clay (probably mainly kaolinite) together with quartz silt and a small percentage of quartz sand (about 4%).

c) Blue Mottle

The presence of Rhizocorallium is very marked in this bed on the foreshore at Staithes (fig. 22) but otherwise the horizon is similar to the Bottom Block.

d) Environment of Deposition

The predominance of mud matrix over grains in the Staithes facies indicates that this facies was formed under quieter probably deeper water conditions than the high oolite deposits to the north, a conclusion which is endorsed by the occurrence of an abundant infauna, and a relatively high proportion of unbroken shell material.

The intercalation of beds of mudstone with wackestone suggests that the Staithes facies stands at the margins of the area of oolite shoals; some ooliths were probably formed 'in situ' but the majority were undoubtedly drifted in from further north. The facies therefore appears to represent a transition between oolite shoal deposits in the north and offshoal mudstone facies further south in the Kettleness facies.

Once again the occurrence of Rhizocorallium may be taken to indicate a shallow and sublittoral environment.

e) Early diagenesis

The percentage of early diagenetic siderite developed as cloudy cored microsparites in the matrix, runs between about 40-70 percent with an average of about 55 percent, but paradoxically the amount of this mineral in the ooliths is relatively small by comparison; the percentage grain sideritisation is only 25 percent. Themajority was probably formed by the carbonation of chamosite, the necessary carbonate being derived by the oxidation of organic material introduced with the faecal debris in the sediment (page 130). The only other early diagenetic replacement spar to occur is pyrite.

Spastolithisation takes place most commonly in the more chamositic beds, reducing the ooliths to elongate chamosite streaks superficially resembling chamosite flakes, usually parallel to bedding butoccasionally at a slight angle due to uneven compaction around burrows.

The majority of pore space is filled with siderite cement identical with that in the previous facies, but in some shelly lenses aragonite may be present.

f) Late diagenesis

Late diagenetic minerals including kaolinite, calcite and sphalerite occur only as replacement spars. Both calcite and kaolinite are fairly widespread in the ooliths; calcite mainly in non-spastolithic grains, kaolinite mainly in spastoliths (plates 35a and 36b). Calcite also occurs as a replacement of the matrix in the vicinity of shelly lenses. Unlike the Upleatham and North Skelton facies, these rocks contain no diagenetic quartz.

g) Conclusions

The majority of iron in the Staithes facies (25-27% in stone dried at 212^{o}F according to Anderson (loc. cit.)) is accounted for by siderite, assuming an average figure of 55 percent for this mineral. The percentage of iron contained therein is around 22 percent leaving 4 percent for chamosite which must therefore constitute approximately 11 percent of the rock.

4. The Kettleness facies

The distribution of the Kettleness facies is shown in figure 39 . As in the case of the Staithes facies the two blocks of the seam are separated by a Middle Shale Band upwards of a foot in thickness. Anderson (op. cit. p. 53) calculated that a reserve of 157 million tons of ore would be available if ironstone mining could be extended two miles south of the present limit into the Kettleness facies but this has never proved feasible.

a) Modal Analyses

The following data was derived from seven rock samples collected from the foreshore at Kettleness. Seven slides were cut and counted to give the average in column three but five further slides taken from grain rich lenses in these rocks were also analysed in preparing columns one and two.

	max. %	min. %	average
Total grains	53.5	5.0	15.0
Ooliths	43.5	3.0	7.6
Intraclasts	2.0	0	0.2
Shells	21.0	0	3.6
Quartz	6.5	0	3.6
Mud Matrix	94.5	46.0	85.0
Primary porosity	3.5	0	0

Kettleness facies, Top and Bottom Blocks

(Total number of thin sections 12, average from 7 specimens)

Superficially the Kettleness facies resembles the Staithes facies, modal analyses indicating an average rock close to the wackestone-mudstone boundary. However, the overall percentage of ooliths is reduced, while the number of shells (predominantly aragonitic species) and more importantly the percentage of terriginous material is increased. The majority of allochems and especially the unbroken shells occur in isolated lenses, probably accumulated by winnowing, but quartz sand grains and occasional mica flakes occur throughout the sediment.

In hand specimen these rocks lack the soft earthy texture and slight green colouration indicative of chamosite in the Staithes facies; instead they are rough and hackly sometimes breaking with concoidal fracture. In part this arises because of the development of interlocking siderite mosaics during early diagenesis but it also appears to be symptomatic of the increasing percentage of terriginous material, both cryptocrystalline quartz and clay mineral, in the facies.

b) Environment of Deposition

Like the Staithes facies the Kettleness facies appears to indicate quiet water deposition, although the distribution of the allochems suggests sufficient water agitation to produce sediment winnowing. The ooliths have clearly been derived through the indrift of material from further north and the percentage of chamosite in the original matrix appears to be declining in favour of terriginous quartz and clay mineral. The Kettleness facies therefore lies outside the region of chamosite oolite shoals, beyond the main area of chamosite formation, and is interpreted as the offshoal facies of the Cleveland Main Seam.

There was, however, sufficient iron in the sediment, either within the clay minerals or as a coating on the surface of the individual micelles to provide large quantities of siderite during early diagenesis.

c) Diagenesis

The majority of early diagenetic siderite in this facies (50-70 percent) therefore appears to have developed at the expense of terriginous quartz and clay rather than that of chamosite. In places a small percentage of siderite cement occurs, but otherwise the only other early diagenetic mineral present is pyrite as a minor replacement spar.

During late diagenesis only calcite was introduced, mainly in the form of small concretions replacing the allochems and matrix in the shelly lenses.

d) Conclusion

No chemical analyses of the Kettleness facies are readily available, but assuming an average siderite level of approximately 60 percent the iron content of these beds may be expected to be around 24 percent.

5. The Hawsker facies

Figure 39 illustrates the manner in which, with the increasing percentage of terriginous material in the Kettleness facies, the Main Seam eventually passes into shale, beginning first with the Bottom Block and then with the Top. To these shales the name Hawsker facies is given. Within the area covered by the present outcrops Hawsker and Howdale Gill are the only localities where bedded ironstone is completely absent, but from an examination of the sections in lower Eskdale and Blackmoor as far west as Rosedale Head, it is clear that the Kettleness facies is close to its limit even in the Top Block. From what has gone previously it may be seen that the Hawsker facies really commences at the 'shale line' in the Middle Dogger Band (fig. 21) gradually assuming more and more importance at the expense of the ironstone facies.

At Hawsker Bottoms the Main Seam is represented by interbedded silty and shaly bioturbitic shales in which may be recognised the approximate equivalents of the Top and Bottom Blocks (fig. 19a). A small percentage of winnowed shell debris is present but the facies is entirely without ooliths.

a) Environment of deposition

The shales of the Hawsker facies closely resemble those of the overlying hawskerense subzone, and are not dissimilar from the silty shales of the subnodosus beds for example. They therefore appear to represent the normal type of terriginous deposit typical of the Middle Lias Shelf in Yorkshire accumulated by slow deposition under shallow sublittoral conditions, unaffected by the oolitic ironstone shoals developing under shallower, more agitated water conditions to the north.

b) Diagenesis

However, the Hawsker facies obviously carried a small percentage of iron, although this was not released from the terriginous debris until the onset of diagenesis, when it was partly concentrated in the form of pyrite through the activity of sulphate reducting bacteria, and partly mobilised to form siderite mudstone concretions mainly within the sandy shales, and occasionally in shell lenses.

Late diagenetic spars such as calcite, kaolinite sphalerite and barytes occur without septariate cracks in the siderite concretions and also as void fillings in the chambers of ammonites. Calcite is also present as a replacement mineral in the aragonitic shell debris.

B. PECTEN SEAM

The distribution and stratigraphic relationship between the three units of the Pecten Seam

(iii) Top Unit

(ii) Eston Shell Beds

(i) Grosmont *Pecten* Unit

are illustrated in figure 17 and discussed on pages 54-56. The distinction between these units is mainly one of fauna, the lithologies being similar in each case, and the seam consisting of alternations of siderite or chamosite siderite mudstones, with spastolithic chamosite wackestones and terriginous shales. Three facies types are therefore recognisable:-

(i) spastolithic chamosite wackestones

(ii) chamosite-siderite and siderite mudstones

(iii) terriginous shales.

1. Spastolithic chamosite wackestones

These are developed in the Eston Shell Beds on the northern escarpment, but occur interbedded with siderite mudstones at this horizon throughout the northern ore field, as well as in the Grosmont *Pecten* Unit around the Guisborough area and at Grosmont itself. They consist of shelly chamosite wackestones in which the ooliths are reduced to elongate chamosite streaks (cf. Dunham in Whitehead et al. p. 39), and closely resemble the chamositic portions of the Staithes facies of the Main Seam, except in the abundance of shell debris.

2. Chamosite-siderite and siderite mudstones

Again these may be compared with similar rock types occurring in the Staithes and Kettleness facies of the Main Seam. They consist of the normal type of siderite microsparite, with percentages of siderite running between 40-70 percent, containing occasional ooliths of variable size (mean 0.3 - 0.6 mm.), more abundant shells and some quartz sand grains.

3. Terriginous Shales

Both the chamosite wackestones and siderite mudstones contain appreciable quantities of terriginous quartz and clay mineral and eventually pass into shales. In the south and south-eastern parts of the area (Rosedale, Fryup Dale, Glaisdale, Grosmont, Hawsker, etc.), the Top Unit and Eston Shell Beds are entirely represented by shales, analogous to the Hawsker facies of the Main Seam.

4. Environment of Deposition

By analogy with the Main Seam the ironstone facies of the *Pecten* Seam are interpreted mainly as shallow water offshoal deposits, perhaps the equivalents of a region of chamosite oolite shoals lying to the north of the present outcrops. However, the *Pecten* Seam differs from the Main Seam in the lateral extent of the mudstone and wackestone facies, and also in the characteristic alternation between siderite mudstone and chamositic shale, so that it is possible that nothing equivalent to the North Skelton or Upleatham facies was ever developed, the chamosite ooliths having been redistributed from local, short lived oolite deposits of no great thickness or extent.

5. Diagenesis

During early diagenesis in the ironstone facies siderite microsparites were developed both by the replacement of chamosite muds and terriginous clays and silts. As usual this process was accompanied by the formation of siderite rinds on the ooliths and possibly by the liberation of opal. Meanwhile in the terriginous shale facies iron was mobilised to form siderite mudstone concretions. Pyrite occurs as an early diagenetic replacement of grains and matrix in both facies, followed during late diagenesis by kaolinite, calcite and sphalerite replacement in the ironstones.

6. Conclusion

Neglecting chamosite and assuming a siderite content of between 40-70 percent the iron content of the *Pecten* Seam may be reckoned at between 16-28 percent compared with values ranging from 23.8 - 30.0 given by the Geological Survey (Anderson op. cit. p. 60-61) on the basis of analyses from Carlin How, Grosmont, Esk Valley and Glaisdale. The analyses given for Upleatham and Hob Hill (loc. cit.) indicate higher percentages of iron but undoubtedly refer to the Two Foot Seam, since the *Pecten* Seam is very poorly represented at these localities. (See Anderson op. cit. p. 38 for note on the way in which the Two Foot Seam is sometimes confused with the *Pecten* Seam).

C. TWO FOOT SEAM

The Two Foot Seam may be described in terms of three facies (see page 46).

(i) Ayton facies } grain rich
(ii) Blackmoor facies }
(iii) Siderite mudstone facies - grain poor

In most localities the Seam consists of intercalations of grain rich sediment, either from the Ayton or Blackmoor facies, with grain poor siderite mudstone (figures 13).

1. The Ayton facies

The distribution of the Ayton facies is shown in figure 14 and corresponds approximately with the area of thick sedimentation already noted on the northern escarpment (page 46). According to Anderson (in Whitehead et al. 1952, p. 55) the seam was tried for ore at a number of localities in this region. Trial analyses at Brotton Mine suggest an iron content in the raw stone running between 28.2 and 30.6 percent (Lamplugh et al. 1920, p. 59, Anderson in Whitehead et al. 1952, p. 59).

a) Modal analyses

	max. %	min. %	average
Total grains	61.2	45.6	54.6
Ooliths	60.0	43.6	52.3
Intraclasts	0.4	0	0.2
Shells	10.0	0	2.1
Mud Matrix	41.0	0.8	18.1
Primary porosity	37.2	5.2	27.3

Ayton facies, (total number of thin sections 7)

By comparison with the grain rich facies of the Main Seam (Upleatham and North Skelton facies) the Ayton facies shows a lower overall percentage of grains, but a primary porosity which is more than twice as high. The average rock from this facies is therefore a sparry packstone, although extensive grainstone lenses occur cross-bedded with the muddier packstones (fig.34b). The high primary porosity arises partly because of the importance of these grainstone lenses, but also as a result of the discoidal nature of the ooliths which allows a much looser grain packing than is possible in the Main Seam (pages 153-154)

Ooliths, consisting of light brown chamosite, with mean diameters around 0.5 mm., constitute the most important grain type, although shells occur very abundantly in some lenses, (figure 13). Terriginous quartz grains are entirely absent.

Dunham (in Whitehead et al. 1952, p. 38) reports the occurrence of a small percentage of chamosite mud in the matrix of the seam at Lingdale but in general siderite occurs alone.

b) <u>Aragonite shell lenses</u>

A distinctive characteristic of the Ayton facies is the occurrence of thin beds and lenses consisting almost entirely of shell debris, together with a small percentage of faecal pellets. Modal analyses indicate percentages of shells ranging up to 94.5 percent of which approximately 85.5 percent are aragonitic. The majority of these shells are disarticulated but largely unbroken, suggesting accumulation under quiet water conditions.

c) <u>Environment of deposition</u>

On the basis of modal analyses the bulk of the Ayton facies, excluding the shell beds and lenses, classes as a highoolite shoal deposit in a similar way to the North Skelton facies of the Main Seam. However, the evidence bearing on the environment of deposition is conflicting. On the one hand the dominance of ooliths in a facies comprising sparry packstones with extensive grainstone lenses, together with the evidence of cross-bedding indicates high energy conditions; on the other the discoidal nature of the ooliths can only be explained by assuming intervals of quiet water (pages 123-124), to which the shell beds are also attributed. This either indicates periodic variations in current activity, or suggests that the ooliths underwent extensive reworking and redistribution under agitated water conditions, following formation under quieter water conditions. The brown colouration of the ooliths might therefore have arisen as a result of reworking under oxidising conditions. Diagenetic evidence, given below, favours the supposition that these rocks accumulated under extremely shallow water conditions, and were in fact exposed to sub-aerial weathering at times (page 291).

Whatever the origin of the ooliths it is clear that they formed at no great distance from their present site; the percentage of these grains, their sorting (page 117) and overall uniformity eliminate the possibility of substantial transport.

It is therefore concluded that the Ayton facies represents an accumulation of quiet water type ooliths, subjected to considerable reworking largely 'in situ' under conditions of shallow water and increased water agitation. The small percentage of intraclasts which occur are attributed to this reworking but in the main the sediments appear to have been too poorly consolidated to give rise to such grains.

d) Early diagenesis

Although siderite microsparites were developed in the matrix of the Ayton facies very little grain sideritisation occurred, apparently because of the high porosity (page 153). Not only did the ooliths lack support from a matrix, but they were never strengthened by siderite 'rinds' and therefore large numbers underwent extreme spastolithisation by extrusion into the intergranular voids. In places the patchy precipitation of aragonite cements, derived from aragonite shells undergoing solution-collapse elsewhere in the seam, halted the process of spastolithisation. Since high salinities are necessary for the precipitation of aragonite spars it is argued (pages 184-185) that horizons which show a concentration of this mineral during early diagenesis must indicate that the oolite shoals were locally sufficiently emergent to develop high salinities as a result of evaporation.

Even after spastolithisation the primary porosity remained in excess of the available siderite cement, so that approximately 5 percent of porosity remained for the precipitation of late diagenetic cement.

e) Lat e diagenesis

This final cementation, together with the filling of shrinkage cavities in the ooliths, and secondary voids created by further solution of aragonite, was carried out by calcite. Void filling was accompanied by replacement in the grains in some cases, but only calcite was involved.

f) Conclusion

Of the iron in the Ayton facies approximately 16.4 percent is accounted for by the chamosite ooliths and a further 17.5 percent by the siderite in the matrix and cement, giving an estimated total of 33.9 percent by modal analysis compared with an average of 33.4 percent in the three samples from Brotton dried at 212^{o}F (Anderson loc. cit.).

2. The Blackmoor facies

The Blackmoor facies occurs in all the exposures of the Two Foot Seam in the south and south west part of the Cleveland area, immediately before the seam is truncated by the margaritatus-spinatum unconformity (see fig. 14). The seam was formerly worked in conjunction with the Top Block of the Main Seam in the Swainby Mines (1857-1860) and there are trial holes in Raisdale, Bransdale, Westerdale, the Fryup Dales and Rosedale.

a) Modal analyses

	max. %	min. %	average
Total grains	63.8	46.4	53.2
Ooliths	47.4	14.6	40.6
Intraclasts	1.4	0	0.5
Aragonite Shells	28.6	2.2	9.9
Calcite Shells	3.0	0	2.2
Mud Matrix	50.2	2.4	28.5
Primary porosity	42.2	0.4	18.3

Blackmoor facies (total number of thin sections 8)

The Blackmoor facies closely resembles the previous facies except in the percentage of shells, which is some 10 percent higher. Once again the seam comprises extensive lenses of grainstone and packstone interbedded with rocks belonging to the mudstone facies, and the modal analyses show an average rock close to the muddy packstone-sparry packstone boundary (fig. 34b).

The ooliths, although slightly less abundant are identical with those of the Ayton facies, and together with the shell debris, give rise to the same kind of loose packing. The majority of shells, comprising approximately 82 percent aragonitic species are exceptionally well rounded, occur throughout the deposit without being concentrated in lenses, and must indicate considerable reworking and abrasion. The other allochems include a small percentage of intraclasts together with faecal pellets and loose chamosite flakes in some cases ~~(fig.)~~. Terriginous sand grains are absent.

b) Environment of deposition

The Blackmoor facies is classed as a mixed oolite deposit and shares with the Ayton facies evidence of a high energy environment, which subjected the constituent shell debris to much breakage and abrasion. The same anomaly exists in regard to the ooliths which again appear to demand quiet water conditions for their formation, and the explanation given is the same as in the former facies.

Like the Ayton facies the Blackmoor facies is attributed to a shallow water environment subject to periodic variations in current activity.

c) Early diagenesis

Both siderite and aragonite occur as early diagenetic spars; aragonite mainly as a cement and siderite both as a cement and a replacement of grains and matrix. The percentage sideritisation in the grains is calculated at 18.7 percent and is therefore far more important than in the Ayton facies.

In consequence although spastolithisation occurs it is less extreme than in the latter deposits.

The siderite cements resemble those of the previous facies and once again were only sufficient to fill aproximately 93% of the available porosity.

d) Late diagenesis

The late diagenetic spars from the Blackmoor facies and the associated mudstone facies are distinctive enough to be absolutely diagnostic; they include dolomite, calcite and sphalerite. Dolomite occurs almost exclusively as a replacement spar in the ooliths and shells and has been observed in every thin section examined from this seam in the Blackmoor area, but never in specimens from the northern escarpment.

Because of the abundance of aragonitic shell debris this facies was subject to extensive solution collapse which not only led to the formation of intriguing pinch and swell textures in the shells themselves (page 168) but so weakened the rock framework that the siderite cements underwent collapse and brecciation, later to be recemented by calcite. The last mineral occurs not only as a cement but also as a void filling after aragonite, and as a replacement of grains of all kinds. As a result of the combined effects of replacement by siderite, dolomite and calcite only about 50 percent of the original chamosite remains in the ooliths. The only remaining late spar of any importance is sphalerite which occurs in small percentages ($>$ 1%) as a void filling and replacement spar in the grains.

e) Conclusion

Following the depradations of the replacement spars the percentage of chamosite left in the Blackmoor facies can be little more than about 20% yielding about 6 percent of iron . The total siderite present in grains, matrix and pores is estimated at 51.8 percent indicating an iron content of approximately 20.6 percent. The total percentage of iron in the Blackmoor facies is therefore taken as 26.6 percent.

3. Siderite Mudstone facies

Shelly oolitic siderite mudstones occur throughout the outcrop of the Two Foot Seam, interdigitating with the grain rich facies just described (figs. 13), but do not usually occur separately as in the case of the Kettleness facies of the Main Seam for example.

a) Modal analyses

	max. %	min. %	average
Total grains	36.4	7.6	20.8
Ooliths	27.6	0.4	17.8
Intraclasts	1.0	0	0
Shells	7.4	0.4	3.0
Mud Matrix	92.2	63.2	79.0
Primary porosity	1.2	0	0.2

'Siderite mudstone' facies, Two Foot Seam (13 thin sections)

The above modal analyses are therefore taken from a number of localities some of them within the region of the Ayton facies, others from the Blackmoor facies and the remainder from the region of thin sedimentation in lower Eskdale and on the coast (page 47).

The modal analyses indicate the way in which many rocks loosely referred to in the field as siderite mudstones are really siderite wackestones. The rocks at present under consideration are completely analagous to the range of ironstone encountered in the Staithes and Kettleness facies of the Main Seam and can only be distinguished with difficulty in hand specimen, although in thin section the shape of the ooliths may be used as a guide to source (page 119).

b) Environment of deposition

The mudstones and wackestones of the Two Foot Seam plainly indicate quieter and probably deeper water conditions than the packstones and grainstones, as in the case of the Main Seam, and are therefore interpreted as offshoal deposits by analogy.

c) Diagenesis

Very little chamosite remains in the offshoal facies of the Two Foot Seam. The matrix consists mainly of siderite microsparite, slightly phosphatic and with around 30-40 percent of cryptocrystalline clay possibly including chamosite, distributed around the crystals and within as distinctive cloudy cores (pages 208-209); the ooliths are almost totally replaced by siderite together with kaolinite, calcite or dolomite in the Blackmoor area. Modal analyses suggest a figure of about 30 percent for grain sideritisation close to the percentage in the Staithes facies of the Main Seam.

d) Conclusion

Assuming an average siderite content of between 60-70 percent, the wackestones and mudstones of the Two Foot Seam probably contain between 24-27 percent iron.

D. RAISDALE SEAM

The basic similarity between the Two Foot and Raisdale Seams, both on a macroscopic and microscopic scale has already been alluded to on pages 48 . The seam may be divided into two facies:- (i) a grain rich facies found predominantly in the south-west of the area in Raisdale and Scugdale, where the seam is at its maximum, and (ii) a grain poor facies, which occupies much of the remaining outcrop ~~(fig.)~~.

1. Grain rich facies

This resembles the Ayton and Blackmoor facies of the Two Foot Seam in many respects, except that it contains a higher percentage of mud matrix and a lower primary porosity, so that the average rock probably lies close to the muddy packstone-wackestone boundary.

Ooliths consisting of pale olive green chamosite are the dominant grain type, have a mean diameter around 0.5 mm., and are always discoidal with a flattening ratio of up to 3:1 in some cases (page 119).

Intraclasts and shells occur in approximately the same proportions as in the Ayton facies.

2. Grain poor facies

The siderite mudstones and wackestones of the Raisdale Seam occur in association with the grain rich packstones, as well as separately in some localities. They are completely analogous with rocks of the same type described in the foregoing sections and further discussion is unnecessary.

3. Environment of deposition

By analogy with the Two Foot Seam the grain rich facies of the Raisdale Seam are interpreted as oolite shoals formed in shallow water by the reworking of quiet water type ooliths, while the grain poor facies are taken to indicate slightly deeper water offshoal conditions.

4. Diagenesis

Siderite is developed as an early diagenetic replacement spar in the matrix (siderite microsparite), and grains (siderite rinds) of both the grain rich and grain poor facies of the Raisdale Seam, sometimes accompanied by pyrite. Cementation was by siderite in most of the packstones, but also by aragonite, and later calcite, in some shelly horizons. Prior to replacement by calcite aragonite occurred as patchy concretions at several levels in the seam, and is taken to indicate periods of emergence as in the case of the Two Foot Seam. Late diagenetic spars include kaolinite, calcite and sphalerite, the former as replacement of the ooliths, the two latter both as replacements and secondary void fillings.

E. AVICULA AND OSMOTHERLEY SEAMS

The facies and distribution of the *Avicula* and Osmotherley Seams are described on pages 30 and 20 respectively; the variation encountered in the *Avicula* Seam is also illustrated diagrammatically in figure 8. Both seams consist principally of bioturbated argillaceous siderite mudstones and wackestones with a small percentage of ooliths usually replaced by late diagenetic calcite and kaolinite. Enough chamosite remains, however, to indicate the original condition of these grains. The *Avicula* Seam contains a large number of shells and like the Two Foot and Raisdale Seams occasionally develops aragonite concretions, now replaced by calcite.

The majority of iron, apparently running between 25.0-29.2 in dried stone from the Grosmont area (Anderson (op.cit. p. 59)), is present as early diagenetic siderite in the matrix. These figures are similar to those given previously for the wackestone-mudstone facies of the Main, *Pecten* and Two Foot Seams and suggest that the average iron content in the siderite wackestone mudstones is around 25 percent.

F. CONCLUSIONS

In 1857 Sorby first proposed a limestone replacement origin for the Cleveland Ironstone, a hypothesis which was later extended to include the French minette ores (Cayeux 1919, 1922) but which has now been long discarded (see page 234). However, Sorby's conclusion was hardly surprising at the time, considering the similarity in texture between minette type ores and oolitic limestones, and the difficulty of identifying the then little known mineral chamosite.

The approach adopted during the foregoing pages has been designed to highlight these similarities while also drawing attention to the differences.

1. Constituent Grain Types

All the main grain types encountered in oolitic limestones, not only ooliths, but shells, intraclasts and faecal pellets, occur in the Cleveland Ironstone Seams and this has enabled the writer to utilise Folk's (1959) concept of limestone classification for the description of ironstones, with very little modification.

Although shells are less abundant than in limestones and although the ooliths and faecal pellets were chamosite rather than aragonite, and the intraclasts reworked ironstones rather than reworked limestones, the textures, origins and implications of these grains are the same. Even on a microscopic scale the structure of the chamosite ooliths is similar to that of recent aragonite ooliths, with alternating layers and laminae of orientated with unorientated mineral in the envelope (pages 109 - 114). The conclusion that the ooliths owe their origin to the operation of the same processes in both cases is inescapable. The exact mechanism which gives rise to the inhomogeneities in the envelopes of aragonite ooliths is debatable at the present time, but probably involves the interaction of physicochemical and biochemical precipitation. However, whatever the mechanism it clearly operated in the chamosite ooliths in exactly the same manner as in their recent aragonite analogues.

There is general agreement among all workers that normal concentric aragonite ooliths are formed by direct precipitation on the seafloor under agitated water conditions. By analogy, therefore, chamosite ooliths must have formed on the sea floor through the action of currents, and not within the sediment as has been suggested by some workers.

There is one physical difference, however, which separates chamosite and aragonite ooliths, which is shape. Whereas aragonite ooliths are profoundly influenced by the shape of their nuclei but tend towards an optimum sub-spherical shape, chamosite ooliths are rarely affected by the shape of their nuclei and have a strong tendency to develop either ellipsoidal or even discoidal shapes. In the writer's opinion these shapes could only evolve under conditions where agitation was only intermittent (page 124). It is therefore concluded that although agitated, the conditions necessary for the formation of chamosite ooliths were less vigorous than those for aragonite ooliths and undoubtedly sublittoral rather than inter- or supra-tidal.

An understanding of the process by which chamosite ooliths form is of paramount importance to the interpretation of the whole environment of ironstone deposition. Since the ooliths form by direct precipitation from sea water, it follows that the constituents for the formation of chamosite must be in solution, colloidal or otherwise, at the sediment water interface. Furthermore, if the water was agitated even intermittently it is most unlikely that reducing conditions prevailed in the bottom waters, although it is possible that each oolith was able to maintain its own reducing 'milieu', perhaps because of the presence of decaying algae within the confines of the oolitic envelope. However, on the basis of thermochemical evidence it appears not unlikely that ferrous iron silicates may be capable of forming under mildly oxidising conditions (pages 317-319).

2. <u>Facies associations</u>

On the large scale as well as on the small, the distribution and petrography of the different ironstone facies is very much what one might expect with a limestone deposit. The complete range of textural classes from grainstone to mudstone (Dunham 1962) is present and arranged in such a manner as to suggest shallow water oolite shoals passing laterally into offshoal mudstones in deeper, quieter waters. The best developed facies array occurs in the Main Seam, where crossbedded mixed oolite packstones pass laterally into high oolite packstones and then into wackestones and mudstones crammed with faecal debris, before finally giving place to terriginous shales.

This kind of association between the chemical sediments closely approximates to that observed in recent carbonate sediments from the Great Bahama Bank for example, where Imbrie and Purdy (1962) describe the association of high oolite and mixed oolite shoals, with skeletal and pellet mud facies, in terms of Folk's (1959) limestone classification. It also resembles the facies arrays described from ancient limestones of Bahamian type, in the Corallian of Yorkshire (Twombley 1964) and Southern England (Wilson 1968a,b) for example. A number of facies commonly developed in oolitic limestones, such as the grapestone and skeletal limestone facies are poorly represented among the present ironstones, but not unknown from other minette type ores.

However, although oolitic limestones may be associated with and pass laterally into terriginous shales in some instances (see for example Schmidt 1965, p. 132) the association is rarely as intimate as that between shales and ironstones in the Cleveland Ironstone Formation. Herein lies one of the most significant differences between oolitic limestones and ironstones. Although, in limestones the precipitation of lime may take place against a background of terriginous sedimentation, either of sand, silt or clay grade, this terriginous material plays no part in the formation of aragonite, whereas it is absolutely essential for the development of chamosite. In the first place the majority of iron is probably carried into the basin of deposition as coatings on the surface of the terriginous grains, and in the second it is only after the breakdown of the terriginous clay minerals during halmyrolysis that sufficient silica and alumina are available for the formation of chamosite.

3. Condensation

Both oolitic limestones and ironstones are usually recognised as condensed deposits, not only by influence from their reworked, shallow water origin, but also on faunal grounds. In each case long periods of time and slow rates of terriginous sedimentation are apparently necessary for formation. Such conditions are absolutely essential for the formation of minette type ores, for considerable lengths of time must be available during which halmyrolytic weathering can effect the necessary iron enrichment. The process involved seems to be one whereby terriginous quartz and clay minerals, originally carrying insoluble ferric iron coatings (Carroll 1958) are preferentially leached from the ironstone shoals, during halmyrolysis and early diagenesis, leaving iron for combination with silica and alumina to form chamosite, or with carbonate radicals to form siderite (see also pages 149, 315-317).

4. Diagenesis

As a rule ironstones are characterised by a greater complexity of mineralogy than limestones. In part this arises because of the large number of iron compounds capable of being directly precipitated both on the sea floor and during early diagenesis as pore fillings, and in part because these phases readily replace each other during early diagenesis. Thus, leaving aside the question of cementation, while limestones mainly undergo diagenetic modification by recrystallisation, ironstones are prone to replacement.

The major exception to this generalisation occurs when limestones undergo dolomitisation, a process which is somewhat analogous to sideritisation in the ironstones, especially when it occurs during early diagenesis (see Schmidt 1965, p. 138).

During late diagenesis the association between ironstones and shales leads to a completely new suite of minerals being available for replacement and void filling in the ironstone seams. By comparison, in many thick limestone deposits, calcite is so abundant that there is little scope for the intervention of other minerals even during late diagenesis. Only where dolomitisation leads to the development of secondary porosity or where thin limestones occur interbedded with beds of different mineralogical facies is there the same potential for late diagenetic modification in the limestones (Schmidt 1965).

Nevertheless, despite differences in mineralogy, many of the textures developed during the diagenesis of limestone find their counterparts in the ironstones which can therefore be interpreted in the light of recent researches into limestone diagenesis.

5. Summary

In the lack of a modern analogue for the marine sedimentary iron ores, recent limestones provide the most satisfactory key for the interpretation of the constituent grains, facies associations and overall environment of deposition, while because of the amount of work carried out on the diagenesis of ancient limestones, these greatly facilitate the interpretation of the sequence of diagenesis.

All that is now necessary is more detailed information on the halmyrolytic process which gives rise to the mineral chamosite and thermochemical data on the stability field of the mineral. Within the next few years, following the discovery of recent chamosite in faecal pellets from the Niger and Orinoco deltas (Porrenga, 1965, 1966, 1967) and the synthesis of the mineral in the laboratory (Caillère et al. 1953, 1955, Caillère and Hénin 1961), both these requirements should be satisfied, by which time the ironstone problem may be regarded as solved.

CHAPTER III ORIGIN OF THE CLEVELAND IRONSTONES

I SOURCE AND TRANSPORTATION OF IRON

Problems concerning the source and mode of transportation of iron are closely connected, because the mechanism by which iron is mobilised depends to a large extent upon environment. The major difficulty arises because trivalent iron is practically insoluble in the presence of oxygen. However, several possible mechanisms whereby iron may be mobilised have been advanced and are reviewed by Taylor (1949, p. 80) and James (1966, p. 39).

A. MOBILISATION OF IRON

1) Under strongly acid or reducing conditions iron may be mobilised as ferric or ferrous salts (Van Hise and Leith 1911, Hayes 1915) but particularly as ferrous bicarbonate (Harder 1919, Borchert 1960, 1965, Braun 1964). In solution its behaviour is relatively easy to predict from thermochemical data (Krumbein and Garrels 1952, p. 15).

2) Provided with a source of organic material iron may be mobilised as a hydrosol under the protection of organic calloids (Gruner 1922, Gill 1927, Moore and Maynard 1929). Under such conditions mobilisation is not restricted by the normal limitations imposed by activity (Krumbein and Garrels loc. cit.).

3) According to Carroll (1958) iron is frequently carried in association with clay minerals, not only within the lattice, but also as an insoluble iron oxide film on the particle surfaces. This mechanism is particularly attractive because it offers a means for mobilising iron under oxidising

conditions without the necessity for protective organic matter.

B. MOBILISATION UNDER CONTINENTAL CONDITIONS

Most workers have inclined towards a continental source for the iron subsequently concentrated in sedimentary ironstones. Because of the Eh characteristics of groundwaters and rivers (Baas Becking et al. 1960, p. 253, 255) transportation is believed to take place mainly in particulate form either as colloids or by association with clay minerals and other detritus. Only under conditions of acid groundwater and reduced Eh such as prevail in swamps and soils in cold humid climates is iron available in solution in sufficient quantities for the formation of ironstones (bog iron ores, bean ores, and iron hard pans), according to Borchert (1960).

However, an increasing weight of evidence exists suggestive of a spatial relationship between deltaic sediments and oolitic ironstones, which may indicate that the iron is continentally derived (Chowns 1966). Pattinson (1964) has described the occurrence of three sideritic chamosite oolites in a cyclothemicc succession of silty shales, siltstones and fluviatile sandstones, from the Namurian of County Durham, which are reminiscent of certain kaolinized oolites from the Coal Measures (Deans 1936, Van Tassel 1955), probably of similar origin. The same kind of association is known from the Liassic succession in Scania, Sweden (Hadding 1933) and from the Middle Jurassic of Yorkshire (Wilson 1948, p. 35) where sandstones, shales, coals and ironstones occur together.

A most important discovery in this respect has been that of fluviatile and deltaic-lacustrine oolitic iron ores in the Oligocene of Kazakhstan, Russia (Yanitsky 1960, Davidson 1961). The shoestring nature of the latter together with the occurrence of freshwater molluscs is incontrovertible evidence of their origin. This correlation is further strengthened by the discovery of goethite and chamosite forming in present day deltaic sediments (Giresse 1965, Porrenga 1965, 1966, 1967).

According to Porrenga (1965, p. 401, 1966, p. 230) much of the iron for the formation of these minerals is carried into the basin of deposition by the rivers as insoluble coatings on clay size quartz and clay minerals. Precisely how much iron is derived in this way, however, is impossible to say; the majority of determinations of the amount of iron carried in rivers only take account of that part in solution (Livingstone 1963, p. 8).

C. MOBILISATION UNDER MARINE CONDITIONS

Borchert (1960) has argued strongly for the case that the mobilisation, transportation and precipitation of iron are all carried out in the marine environment. Sea water may possess greater potential for the mobilisation of iron salts than freshwater. (Baas Becking et al. 1960, p. 258) and Borchert believes that given a high partial pressure of CO_2 the mobilisation of iron bicarbonate might assume great importance. This is apparently the case where gyttja type sediments are forming in the Barentz Sea at the present time (Trofimov 1939) and may have occurred on a large scale in the geological past, at times when, through the absence of polar ice caps, the deep-sea bottom waters were deprived of oxygen rich polar water.

However, in modern seas the amount of iron in solution is small, and as with rivers the greater part occurs in particulate form (Cooper 1935).

D. MOBILISATION OF IRON THROUGH CONTEMPORANEOUS VOLCANISM

In regions of crustal instability the development of ironstones may be associated with contemporaneous igneous activity, although a genetic connection is often difficult to prove (James 1966, p. 47). Nevertheless, a number of ores of the Lahn-Dill type appear to have derived their iron from volcanic sources (Harder 1964).

However, Europe is known as a stable shelf area throughout the Mesozoic and none of the ironstones have been shown to be associated with contemporaneous volcanics. This possibility may therefore be ruled out not only for the Cleveland ironstone seams but for the Mesozoic ironstones in general.

E. SOURCE OF IRON IN THE CLEVELAND IRONSTONE FORMATION

In the present deposits there is no direct evidence to indicate the source of iron. The ironstones are clearly of shallow water facies, but the iron could have been transported either from a marine or continental source. However, the point of view is taken that a continental source of iron is the more likely.

The possibility of a nearby river delta was postulated by Dunham (1960), but unfortunately no direct evidence for an impinging delta complex exists in the present outcrops, and Hallam's (1966) supposition that the reworked shales and siltstones of the Middle Lias are distal pro-delta deposits can only be tentative at present. The question of sediment derivation is therefore a difficult one. The presence of large river deltas in the Baltic and Scandinavian areas undoubtedly played an important part in the make up of the sediments deposited in the North German Basin with its extension into Yorkshire, but it is unlikely that these deltas were as extensive as Hallam (op. cit.) has supposed.

If the iron was of continental origin, carried as calloids or in association with clay minerals, deposition might be expected to proceed fairly rapidly upon entry into the marine environment as a result of flocculation. Only under such conditions could the desired concentration of iron be approached. The source is therefore likely to have been more local and at the present time a Scottish-Pennine island ~~(fig.)~~ appears to provide the most appropriate site (~~pages~~ Chowns 1966). The iron was therefore probably derived by the erosion of early Liassic sediments and Permo-Triassic red beds. The climate was probably tropical or subtropical (oxygen-16/oxygen-18 ratios, determined from belemnites from the overlying Grey Shales of the Upper Lias, indicate a palaeotemperature of about 20°C (Smethurst et al.)) and a heavy vegetation is suggested by the abundance of wood debris throughout the formation.

II DEPOSITION OF IRON

A. CONCENTRATION

The assumption of an iron rich source does not appear to be essential for the accumulation of a sedimentary iron ore. According to Gruner (1922) the amount of iron carried by rivers is quite sufficient for the formation of ironstones provided some means of concentration is available.

Most recent concentrations occur under continental conditions either in low latitudes as a result of lateritic leaching or in high latitudes as bog-iron ores forming in freshwater lakes and swamps. In the past, however, the coincidence of ironstones with ancient shorelines, around the London-Ardennes landmass and the Morvan in the Jurassic for example (Gignoux 1955, p. 331), or with transgressive or regressive deposits, indicates that the littoral zone provided a most important site for concentration. Evidence of shallow water and current activity abounds in all the minette type ores ~~(page ———).~~ Although, Borchert (1960) has pointed to the occurrence of ironstones in North Germany which were apparently formed at a distance from land, from their oolitic and intraclastic nature they are clearly of shallow water origin (Braun 1964).

Bearing in mind the fluviatile ironstones of the northern Turgai and northern Aral'sk districts of Kazakhstan (Davidson 1961) it appears that a complete spectrum of ironstones ranging from non-marine to marine exists.

In all these facies concentration is effected by the separation of iron from detrital sediment by one or more of several possible processes:-

(i) In the first place the maturity, climate and weathering characteristics of the source obviously play an important part in determining the size and composition of the detritus as well as the amount of particulate iron reaching the basin of deposition in suspension (as films on clay minerals and quartz grains).

(ii) The concept of a 'clastic trap', some kind of physical or hydrodynamic barrier, has arisen as an attempt to explain the separation of terriginous sediment from chemical sediment (Huber and Garrels 1953; Castano and Garrels 1950).

(iii) Sinc the majority of iron reaches the basin of deposition in intimate association with the finer grades of terriginous sediment chemical reactions are essential before separation will occur (Carroll 1958, p. 21). The essence of Borchert's hypothesis (1960) for the formation of sedimentary iron ores is that iron may be selectively mobilised from detrital marine sediments, but it is possible the reverse process may obtain; that iron may be enriched through the leaching of terriginous debris.

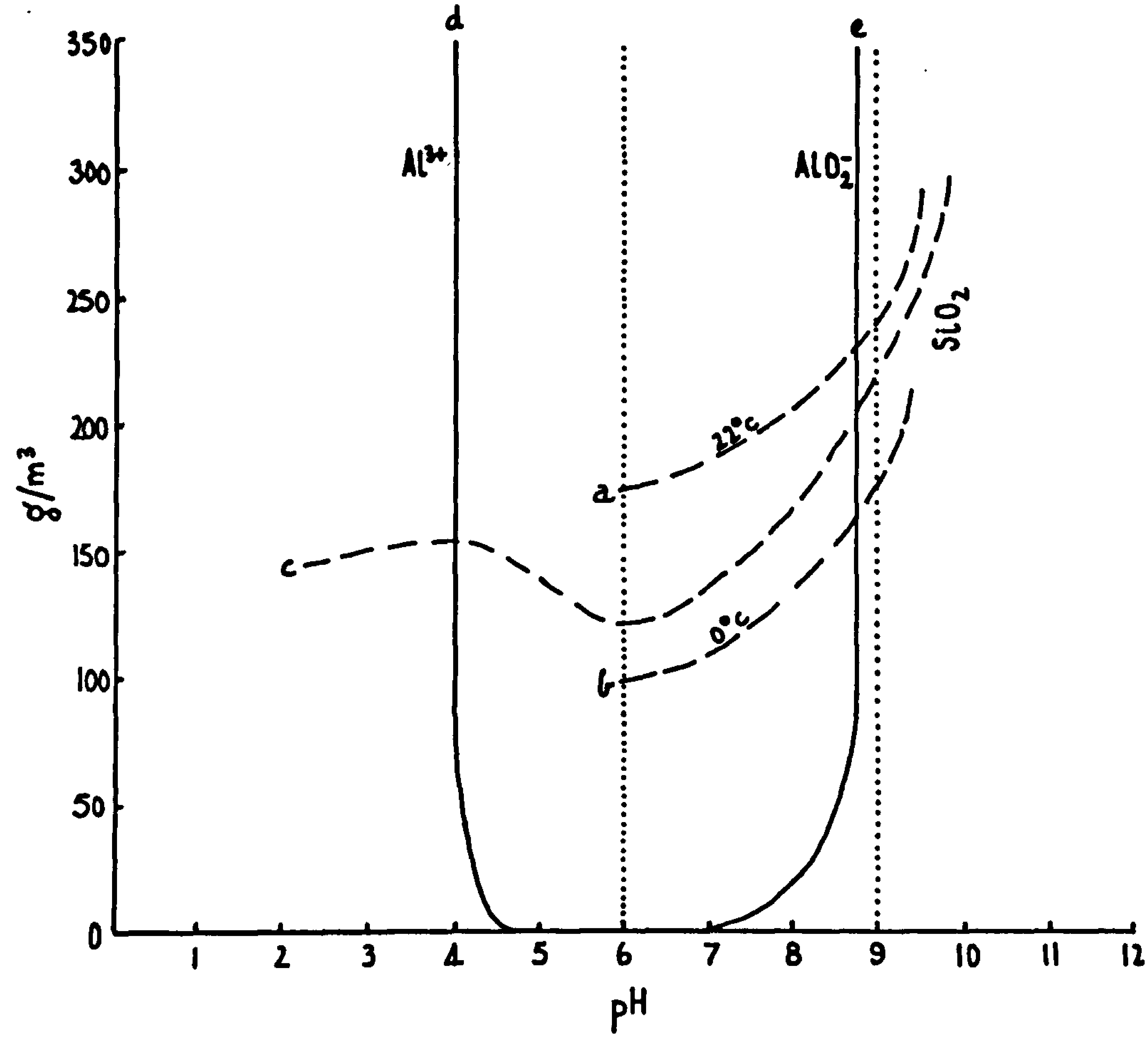
B. SEPARATION OF CHEMICAL FROM TERRIGINOUS SEDIMENT IN THE CLEVELAND IRONSTONE FORMATION

Throughout the deposition of the Cleveland Ironstone Formation the supply of terriginous sediment to the Yorkshire basin remained mainly in the silt and clay grades (pages 147- 149). Sufficient iron was available for the formation of siderite mudstone concretions in the shales during diagenesis and for the development of bedded ironstones at six horizons.

However, there are grave difficulties in the application of the principle of a 'clastic trap'. The Main Seam, *Pecten* Seam and *Avicula* Seam all pass laterally into silty shales without sign of physical barriers, and although a hydrodynamic division clearly exists between oolite facies, on the one hand, and mudstone and shale facies on the other, no simple correlation exists. Despite the occurrence of muddy matrices in the ironstones the percentage of fine grained quartz and detrital clay present is suspiciously low. It cannot be argued therefore that terriginous debris has been winnowed away with the fine fraction. The passage of ironstone into shale is not the result of terriginous dilution neither is it the result of a massive influx of iron sediment derived from elsewhere and superimposed upon a background of terriginous sediment (pages 302-304). Rather, fine grained quartz and clay mineral was selectively removed in solution or in part reconstituted as the mineral chamosite.

Unfortunately the effects of corrosion may only be identified with certainty when they are the result of replacement; when a pseudomorph or partial pseudomorph after the original mineral is present. If corrosion is not accompanied by replacement it may be difficult or impossible to recognise. Corrosion textures are therefore most important in the secondary ironstone facies (carbonate and sulphide facies): the corrosion and replacement of quartz grains and clay minerals is a characteristic feature of ironstones where secondary calcite, siderite or pyrite are developed (pages 226); see also Caillére and Kraut (1954), Bübenicek (1964) and Bartholomé (1966). In the primary ironstone facies, chamosite does not form pseudomorphs after quartz, neither is it possible to observe the replacement of detrital clay. However, the overall purity of these facies makes it probable that the same process has taken place, possibly on the sea floor without replacement, rather than within the sediment by replacement as in the sideritic facies.

The process of iron enrichment in the Cleveland ironstones may therefore be somewhat akin to that of lateritisation by which silica and, to a lesser extent, aluminium are mobilised by hydrolytic weathering and then removed provided the pH of the weathering system is sufficiently high (Keller 1957, p. 21). Figure 43 illustrates recent work which shows that under alkaline conditions the solubilities of both SiO_2 and AlO_2^- (or more probably some complex of Al^{3+} - OH^- according to Borchert



SOLUBILITIES OF SiO_2 AL^{3+} & ALO_2^-

a, b AFTER OKAMOTO ET AL 1957
c AFTER ALEXANDER ET AL 1954
d e AFTER BRAUN 1963
(SEE BORCHERT 1965 175 FOR DISCUSSION)

FIG. 43.

1965) increase rapidly and that they may be removed in solution as colloids.

Given conditions of prolonged submarine weathering, therefore, such as are envisaged in the condensation of so many minette type ores, and alkaline pHs (in the range 7-9) leaching offers a feasible mechanism for iron enrichment.

C. THE PRECIPITATION OF IRON

For an understanding of the behaviour of iron within the basin of deposition it is necessary to know the fields of stability of the iron minerals and their activities in terms of Eh and pH. Theoretical stability relations for iron oxides, sulphides, carbonate and silicates are given by Krauskopf (1957), Garrels (1960), Garrels and Christ (1965), while the stability fields for iron minerals precipitated in the laboratory are given by Huber and Garrels (1953), Huber (1958), and Castano and Garrels (1958).

Figures 40 a & b are taken from Krauskopf (op. cit. p. 64) and Garrels and Christ (op. cit. p. 228) and show the stability boundaries between mineral pairs in the first case, and the stability fields between phases in the second, both under a different set of conditions. These are as follows:-

In figure 40a the field boundaries are based on: total carbonate 2×10^{-3}M (aqueous concentration of pH 8 in equilibrium with atmosphere);

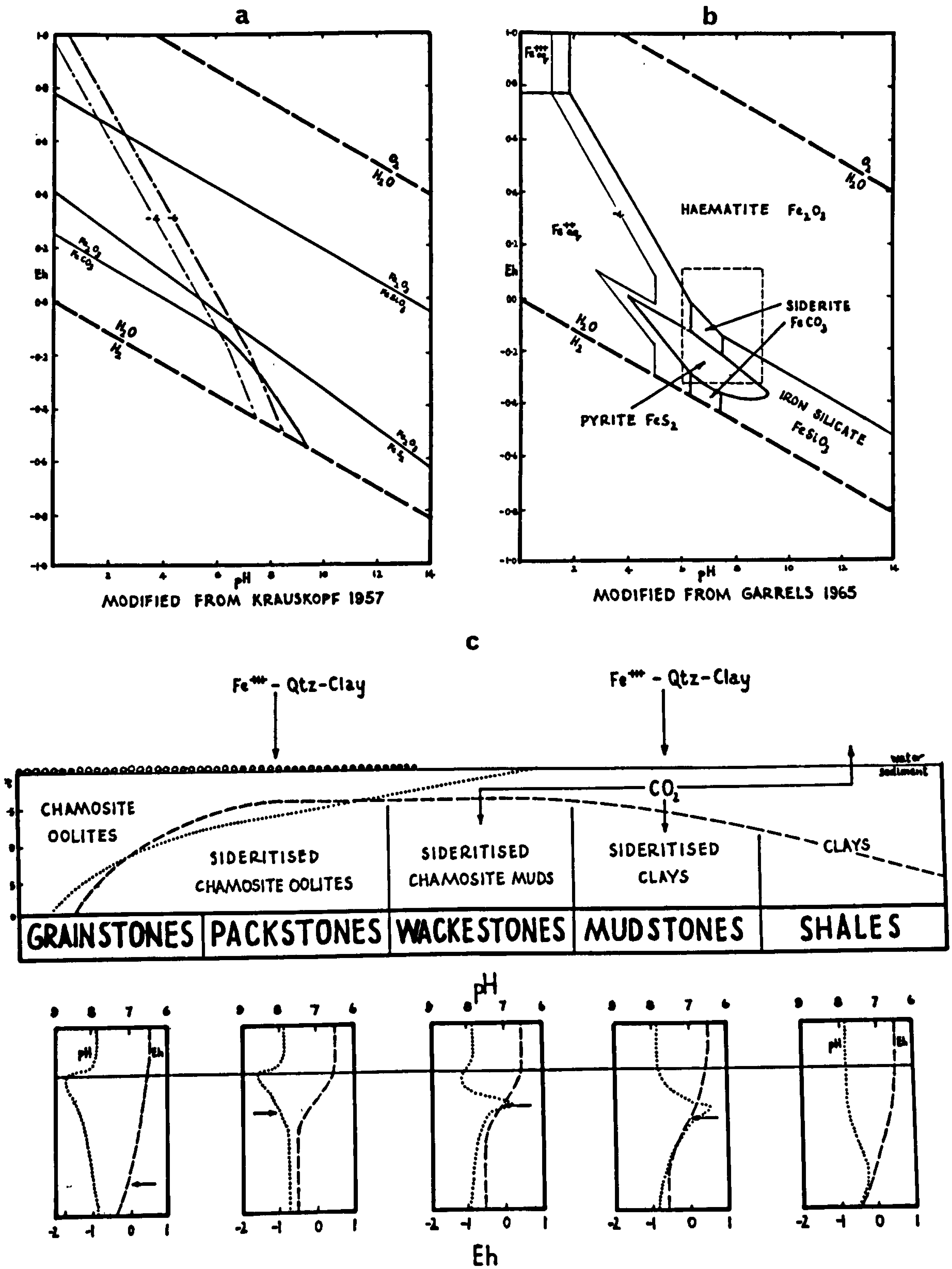


FIG. 40. TEXTURAL AND MINERALOGICAL FACIES OF IRONSTONE DEPOSITION.

total sulphur $10^{-1}M$; total silica $2 \times 10^{-3}M$ (amount soluble in water, mainly as H_4SiO_4 at 25^oC).

In figure 40b the total carbonate is raised to $10^{0}M$; total sulphur is reduced to $10^{-6}M$; total silica is equal to that in equilibrium with silica glass (amorphous silica).

The main difficulty in applying these theoretical stability relations arises because the compounds used in the thermodynamic calculations do not correspond exactly to the natural phases, and no account is taken of metastable phases. In particular iron metasilicate ($FeSiO_3$) is a poor substitute for chamosite and the other iron aluminium silicates. Precisely what the effect of adding alumina would be, is unknown, but since its mobility is strongly affected by pH it may be that alkaline conditions are a necessary condition for the formation of chamosite. However, in general it may be assumed that the more complex mineral compounds have somewhat larger stability fields than their simple equivalents.

The following conclusions may be drawn regarding the precipitation of the iron compounds:-

(i) The mineral phases precipitated are strongly dependent upon Eh and only to a lesser extent on pH.

(ii) The precipitation of iron oxides takes place over a broad field ranging from oxidising to reducing mainly dependent upon the concentration of silica and sulphide sulphur.

(iii) Provided the concentration of silica is sufficient the formation of iron silicates will take place under mildly oxidising conditions as well as under reduced.

(iv) The stability realm of siderite is exceptionally small except at very high carbonate concentrations. Even in such conditions siderite will only form at reduced Eh when the concentration of silica and sulphide sulphur is low.

(v) By contrast with siderite, the pyrite field also formed under reducing conditions is remarkably persistant even at low sulphur concentrations.

The implications of this information, combined with the Eh and pH characteristics of other chemical sediments have been summarised by Krumbein and Garrels (1952, p. 26)in terms of a classification of sedimentary end-member associations. From the point of view of ironstone formation the position of the limestone fence at pH 7.8 (activity of calcium ion 10^{-3} mols/litre) is particularly important. It means that for the development of pure sedimentary ironstones the environment must be undersaturated in calcium ion and must evolve in such a way as to preclude the precipitation of calcium carbonate; any increase in pH must be accompanied by a markedincrease or decrease in Eh. (Krumbein and Garrels 1952, p. 15).

D. NATURAL FACIES ASSOCIATIONS

The theoretical stability relations between different iron phases fit natural occurrences so well that the most useful classification of ironstones is achieved on the basis of mineral facies. A complete facies array indicating the characteristic textures involved and the probable mode of origin is given below in tabular form.

FACIES	TEXTURE	ORIGIN	
IRON OXIDE	GRANULAR (OOLITIC)	SHORE	PRIMARY
IRON SILICATE		↓	
IRON CARBONATE	NON-GRANULAR	DEPTH	SECONDARY
IRON SULPHIDE			

The term granular is used to describe grain rich rocks (grainstones, packstones and wackestones) as distinct from grain poor mudstones and shales; primary refers to minerals deposited above the sediment-water interface, secondary to those below. Similar arrays are shown diagrammatically by James (1954) for Precambrian iron-formations and by Borchert (1960, 1965) for Phanerozoic ironstones. The above scheme differs from that of Borchert (op. cit.) in the position of the silicate facies, which Borchert places between the carbonate and sulphide facies, and in the exclusion of a chert facies, rarely if ever developed in association with Phanerozoic ironstones.

No example is known of a complete array of major facies passing laterally one into another (James 1966, p. 15) but penecontemporaneous associations between adjacent facies are not uncommon (Braun 1964, p. 27-40).

E. FACIES ASSOCIATIONS IN THE CLEVELAND IRONSTONES

No primary iron oxides occur in these ironstones and therefore the oxide facies may only be said to exist in so far as it is a product of recent weathering. The constant association is one between chamosite as a primary mineral in the ooliths and matrix and siderite as the principal diagenetic constituent, mainly located in the matrix and cement. The grainstone and packstone facies are the main repositories of chamosite, the mudstone facies of siderite. In general terms, therefore the grainstones and packstone may be ascribed to the iron silicate facies, the mudstones to the iron carbonate facies, with the wackestones standing at the boundary. Pyrite occurs scattered through all these rock types, but only in the Sulphur Band may a sulphide facies be said to exist and even here it appears to have been superimposed through the diagenesis of beds above the Main Seam rather than a product of the original depositional environment (Pages 197- 202). Finally the spectrum is completed by the development of contemporaneous shale facies, where terriginous sediment dominates, in the Main, *Pecten* and *Avicula* Seams

Figure 40c is an attempt to illustrate the relationship between the chamositic, sideritic and terriginous facies as they occur in the Cleveland ironstones. The diagram represents a profile through an area of chamosite oolite shoals, with grainstones and packstones passing laterally into offshoal wackestones and mudstones, and then into shales, an idealised facies arrangement which is approximated fairly closely by the Main Seam (see fig. 39). Iron is presumed to have been deposited along with quartz and clay minerals and then enriched by the leaching of the terriginous fraction. A dashed line indicates the position of the oxidation-reduction boundary in the profile, while the stability field of chamosite is delimited by a dotted line. In the Eh, pH diagrams given below, this boundary is equated with a critical pH value of 8, below which it is assumed that:-

(i) Chamosite will not form because of the immobility of alumina.

(ii) Chamosite will be replaced by siderite, during diagenesis, if the Eh is below 0.

This is clearly an oversimplification however; the precise effect of pH on the formation of chamosite is unknown, and the effect of variations in the partial pressure of CO_2 are neglected.

1) <u>The grainstone and packstone facies</u>

From the abundance of ooliths in the grainstone and packstone facies these are believed to represent fossil oolite shoals (pages 141-142) which were the site of chamosite formation, since chamosite is clearly the primary mineral of the oolitic envelopes (pages 300-302 and see Hallimond 1925, p.). The mineral appears to have been precipitated both physicochemically and biochemically (pages 111-114) and it is argued that oxidising conditions prevailed through circumstances of gentle water agitation.

Chamosite is believed to develop through the interaction of clay with ferrous iron (Hallimond 1925, p. 98), part of the silica and alumina mobilised in the surface layers of the sediment being reprecipitated under the conditions of oolith formation, possibly because of a rapid fall in pH across the sediment water interface. Precisely what conditions are necessary for this reaction are unknown, but it is postulated that pH is the important factor because of its effect on the activity of aluminium and to a lesser extent silicon. The leaching of detrital sediment from these facies appears to be particularly effective (pages 263-273) and it is tempting to correlate high pHs in the surface layers of the sediment with the presence of algae or bacteria (pages 124- 126).

Siderite develops during early diagenesis as a replacement of both grains and matrix in the packstone facies, but may not appear until much later, when cementation takes place, in the grainstone facies. It is concluded, therefore, that the presence of mud has a decisive effect on the course of sideritisation, probably because it impedes circulation within the sediment and therefore encourages the onset of reducing conditions. However, variations in the relative sideritisation of grains and matrix indicate the interplay of a number of factors including not only the oxidation-reduction potential, but the hydrogen ion concentration and the pressure of carbon dioxide (pages 318-319).

2) The wackestone facies

The wackestone facies arises as a result of mixing between the grainstone-packstone facies on one hand and the mudstone facies on the other, either through current activity or because of organic burrowing. The increase in mud therefore brings with it increasing quantities of faecal debris both as burrow fillings and pellets, and the percentage of ooliths relative to other grain types declines (pages 274 - 279).

Extensive sideritisation takes place shortly after burial especially in the matrix and it may be impossible to distinguish the primary constituents of the mud. In the Main, Pecten and Avicula Seams relics of chamosite mud remain but not so in the other seams where sideritisation is complete. During this process chamosite ooliths ~~lo~~se their distinctive green or brown colouration, probably due to the removal of iron, and the internal structure becomes obscure as the result of replacement by opal and kaolinite (pages 235, 239). It is possible that these replacements indicate the inability of the pore waters to remove the silica and alumina mobilised by the breakdown of terriginous quartz and clay probably as a result of the decrease in pH initiated by the development of reducing conditions.

3) The mudstone facies

With the exception of the chamosite mudstones of the Black Hard, the mudstone facies are always characterised by the presence of siderite. The mineral forms distinctive microspars and is clearly of secondary origin so that the main problem lies in the nature of the original muds (pages 144- 149). In some cases they may have been chamosite but in many it is probable that siderite developed directly by the replacement of terriginous sediment. The process of leaching may have begun before the onset of sideritisation but continued during replacement despite what appear to be unfavourable pH conditions. The effectiveness with which impurities were expelled from the growing crystals varied; in particular the presence of cloudy cores indicates that the removal of clay was less effective during early growth than later (pages 208- 210). However, the process was never as complete as in the chamositic facies and in consequence it has never proved possible to extend ironstone workings into these rocks.

The Eh and pH characteristics of this facies may have been somewhat analogous to modern day gyttja type sediments (Trofimov 1939). The development of siderite indicates high concentrations of CO_2 derived from the oxidising decomposition of organic matter, contained in the surface layers of sediment in an abundant supply of faecal material (pages 130- 132). Following the onset of reducing conditions iron would have been mobilised and then reprecipitated as the carbonate with rising pH.

4) <u>The shale facies</u>

The sediments of the terriginous shale facies consist largely of silt and clay sized quartz and clay minerals of which the most important is kaolinite ~~(pages)~~. In most cases the supply of iron relative to terriginous material was undoubtedly lower than in the ironstone facies, but not necessarily so, especiallywhere shales pass laterally into ironstones as in the case of the Main Seam (pages 282-283).

Although the angularity of the quartz grains may be taken to indicate a certain amount of corrosion (pages 226) it is postulated that the degree of terriginous leaching was much lower than in the ironstone facies partly because of a lower hydrogen ion concentration and partly because siderite did not develop as a replacement mineral during early burial. There are several possibilities for the failure of new iron minerals to develop under these circumstances:-

(i) Iron may have been mobilised as a result of reduction, but removed in solution before it could be combined to form either chamosite or siderite (Carroll 1958, p. 22).

(ii) The onset of reducing conditions in the sediment may have been delayed so that the iron oxide films were retained on the clay minerals until later in diagenesis, (Carroll 1958, p. 22).

(iii) The oxidising decomposition of organic material may have been carried to completion before the onset of reducing conditions necessary for the formation of either siderite or pyrite.

Figure 40c illustrates a combination of possibilities (ii) and (iii). It is assumed that reducing conditions were delayed because of improved circulation in the sediment and that in consequence CO_2 from the oxidation of faecal material was lost before it could be combined with ferrous iron. Only in the immediate vicinity of burrows were reducing conditions able to develop, and here pyrite formed.

The greater part of the iron in these sediments was therefore retained in association with the detrital fraction until the onset of compaction. The effect of compaction was probably to restrict the pore waters thus finally mobilising the iron which migrated to horizons where CO_2 was being evolved, again probably as a result of rearrangements resulting from compaction, and segregated to form siderite mudstone concretions.

F. THE ROLE OF HALMYROLYSIS AND EARLY DIAGENESIS IN THE DEPOSITION OF IRON

Although the limestone replacement hypothesis for the origin of ironstones (Sorby 1856, 1906; Cayeux 1919, 1922) has now been generally abandoned a major controversy still exists over which iron minerals should be regarded as primary and which secondary. As pointed out by Taylor (in discussion to Bubenicek 1964, p. 131) it is possible to observe replacement relationships between almost all the minerals which occur in sedimentary iron ores but more difficult to define criteria for primary deposition.

At the heart of the problem lies the origin of the two minerals chamosite and siderite, as they appear in the ooliths and matrix. French workers (Caillère and Krout 1954, Bubenicek 1960, 1964) have taken the extreme view that both chamosite and siderite are to be regarded as secondary minerals formed by the replacement of ferric oxides or hydroxides, while since the work of Hallimond (1925) and Taylor (1949)

British geologists have regarded chamosite as mainly primary and siderite as at least partly so. That such a controversy should exist is not really surprising considering our ignorance over the questions of source, mobilisation, transportation and precipitation of iron, arising from the absence of recent analogues for the minette type ores.

Terminology is also a problem. Close to the sediment-water interface, where the reactions necessary for the formation of the iron minerals appear to take place, the processes of deposition and diagenesis meet and overlap so that terms like primary and secondary become difficult to apply. An open system is involved in which minerals and solutions above and below the sediment-water interface attempt to reach equilibrium through a constant exchange of ions; some minerals disappear through solution or replacement while others take their place as pseudomorphs or through re-precipitation.

This whole process is so similar to that of terrestrial weathering that it has been called submarine weathering or halmyrolysis (Hummel 1922, p. 41). Like terrestrial weathering it is both destructive and constructive at the same time (Keller 1955, p. 5-9).

Throughout the preceding pages a tacit distinction has been made between those minerals and structures which formed above the sediment-water interface and those which formed below, and between those minerals which formed by direct precipitation and those which formed by replacement (~~table~~ fig 38).

Thus because the oolitic structure of these ironstones has been accepted as depositional (pages 111-114) and because chamosite is in every way concordant with this structure, it is regarded as having formed by direct precipitation above the sediment-water interface (pages 322-323) while both on thermochemical and textural grounds siderite mud is believed to have formed by replacement below the sediment-water interface. The one mineral is described as halmyrolytic, the other as early diagenetic. Even so, the formation of both chamosite and siderite is regarded as part of one penecontemporaneous process, involving the interaction of sediments both above and below the sea floor.

The process was destructive in so far as terriginous material was leached, replaced and reconstituted in the formation of ironstone facies, but constructive to the extent that iron was enriched to form new minerals.

APPENDIX I STRATIGRAPHIC COLUMNS

STAITHES (NZ 793188)

Zone of *Dactylioceras tenuicostatum* (pars.)

61	Dark grey shale with six beds of siderite mudstone concretions	8' 10"
60=	Bed of 2" calcite mudstone concretions (discrete to conjugate)	
59	Dark grey shale	2' 0"
58	Laminated sideritic shale	3"
57	Dark grey shale	1' 0"
56	Laminated sideritic shale	3"
55	Medium grey silty shale; (*Pseudopecten equivalvis*, belemnites, wood)	1' 9"
54	Bed of 2" discrete calcite mudstone concretions (*Pholodomya* sp., growth position, *Pinna* sp., growth position, *Pseudopecten equivalvis*, belemnites)	
53	Medium grey silty shale	1' 5"
52	*Sulphur Band*. Laminated dark to light grey pyritic shale. Replaced by siderite in places (wood)	6"

Zone of *Pleuroceras spinatum* 21'2"

Subzone of *Pleuroceras hawskerense* 6'7"

51	Medium grey silty shale with small scattered siderite mudstone marbles (*Unicardium subglobosum*)	1' 6"

50	Bed of tabular siderite mudstone concretions, with engulfed calcite mudstone concretions and "beef". (*Pleuromya costata* -growth position, *P. hawskerense*).	10"
49	Light grey silty shale with small siderite mudstone marbles, and lenticles of rippled calcareous siltstone (*P. hawskerense*).	1' 3"
48	Medium grey silty shale	3' 0"

Subzone of Pleuroceras apyrenum 14'7"

47	*MAIN SEAM - TOP BLOCK* Alternations of oolitic siderite mudstone and thin chamositic chamosite oolite (*P. apyrenum*, *P.hawskerense*, *Pseudopecten equivalvis*, *Pholadomya sp*. growth position, belemnites, wood, abundant trace fossils)	2' 6"
46	Sideritic, chamositic shale	1' 0"
45	*MAIN SEAM - BOTTOM BLOCK* As the top block but more sideritic (*Pholadomya* growth position, wood, abundant trace fossils)	3' 2"
44	*BLACK HARD* Siderite mudstone and spastolithic chamosite oolite with *Rhizocorallium*.	1' 4"
43	Sideritic chamositic shale	1' 5"

42	Siderite mudstone	6"	PECTEN SEAM TOP UNIT	1' 8"
41	Chamositic sideritic shale	5"		
40	Siderite mudstone	5"		
39	Chamositic sideritic shale	4"		

38	Shelly siderite mudstone	4"	PECTEN SEAM BOTTOM UNIT	3' 6"
37	Shelly chamositic sideritic shale	6"		
36	Shelly siderite mudstone	5"		
35	Shelly chamositic sideritic shale	3"		
34	Shelly siderite mudstone	2"		
33	Shelly, pebbly chamositic sideritic shale	4"		
32	Shelly siderite mudstone	6"		
31	Chamositic sideritic shale very fossiliferous at base.	1'0"		
	Fossils include Pholadomya, growth position, Pseudopecten equivalvis, Gresslya sp., Ostrea, Oxytoma cygnipes, Plicatula spinosa, Tetrarhynchia tetrahedra, belemnites, wood, abundant trace fossils Rhizocorallium. No ammonites			

Zone of Amaltheus margaritatus (pars.)

Subzone of Amaltheus gibbosus 29'0"

30	Dark grey shale	1' 7"
29	TWO FOOT SEAM - shelly oolitic siderite mudstone. Pebbly at base (A. gibbosus, A. margaritatus, Pseudopecten, dwarf Protocardia truncata, belemnites, wood.)	1' 4"
28	Dark grey pyritic shale (Oxytoma inequivalvis)	5' 8"

27	Bed of 2" poor conjugate siderite mudstone concretions (A. gibbosus, A. margaritatus)	
26	Dark grey pyritic shale (Oxytoma inequivalvis, wood)	3' 11"
25	RAISDALE SEAM - shelly oolitic siderite mudstone (Protocardia truncata, Pseudopecten, belemnites)	10"
24	Dark grey shale and very light grey silt in graded laminations, with longitudinal current scours and other sedimentary structures (5'0") (Amaltheus sp. Pseudopecten, Ostrea, wood) passing down into dark grey pyritic shale with Pentacrinus ossicles.	11' 4"
23	Bed of 2" poor conjugate siderite mudstone concretions.	
22	Dark grey pyritic shale with thin shell bed at base (Oxytoma cygnipes, Pseudopecten, Ostrea, wood)	4' 4"

Subzone of Amaltheus subnodosus 23'4"

21	Dark grey shale	8"
20	AVICULA SEAM - BOTTOM BLOCK - shaly oolitic siderite mudstone; fossiliferous and conglomeratic especially at the base (A. subnodosus, Pseudopecten, Ostrea, O. cygnipes, O. inequivalvis, Protocardia truncata, Gresslya, belemnites, wood)	1' 10"
19	Conglomeratic shell bed overlain by tabular siderite mudstone concretions (Entolium, P. truncata, Pseudopecten, Ostrea, O. inequivalvis)	3"
18	Light grey silty shales; strongly reworked by fauna. With large 6" siderite mudstone concretions at top and bottom. Shelly lenses (P. truncata, O. inequivalvis, Pseudopecten, belemnites, wood)	1' 8"

17	Conglomerate of siltstone and limestone pebbles set in a silty shell bed matrix of Entolium, P. truncata, Ostrea, Pseudopecten, belemnites. Pebbles show strong siderite replacement (A. margaritatus, A. subnodosus)	2"
16	Light grey silty shale; strongly reworked by fauna with shelly lenses (P. truncata)	2' 8"
15	Bed of 4" discrete scattered siderite mudstone concretions (A. subnodosus, Gresslya, in growth position)	
14	Light grey silty shale; as above (O. inequivalvis)	1' 2"
13	Bed of 4" discrete to conjugate siderite mudstone concretions (A. subnodosus, Gresslya, in growth position)	
12	Medium grey pyritic shale (O. inequivalvis, Pentacrinus, wood)	9"
11	Bed of 4" discrete to conjugate siderite mudstone concretions (A. subnodosus, A. margaritatus, Gresslya in growth position)	
10	Medium grey pyritic shale (A. margaritatus, O. inequivalvis, P. truncata, belemnites, wood)	3'10"
9	Dark grey pyritic shale (O. inequivalvis, P. truncata) separated from above by strong parting.	4' 9"
8	Bed of 3-4" discrete to conjugate siderite mudstone nodules (P. truncata, O. inequivalvis, Gresslya in growth position, wood)	
7	Dark grey pyritic shale. (A. margaritatus, P. truncata, O. inequivalvis, Modiola scalprum, belemnites)	1' 2"

6	Bed of 3"-4" discrete to conjugate siderite mudstone nodules (P. truncata, O. inequivalvis)		
5	Dark grey pyritic shale (Pseudopecten, O. inequivalvis)	1'	0"
4	Bed of 4"-5" discrete to conjugate siderite mudstone nodules (A. subnodosus, P. truncata)		
3	Medium grey shale passing down into light grey silty shale (O. inequivalvis, P. truncata, A. subnodosus, wood)	1'	7"
2	Highly fossiliferous 6" siderite mudstone nodules with calcareous coats (A. subnodosus, A. margaritatus, A. wertheri, P. truncata, O. inequivalvis, Cardita multicostata, Entolium)		
1	Light grey silty shale passing down into medium grey shale (Pseudopecten, wood)	1'	10"

0	OSMOTHERLEY SEAM - Irregular oolitic siderite mudstone, with protruding nodules from below		3"

ROCKCLIFF (NZ 757195)

Zone of *Dactylioceras tenuicostatum* (pars.)

31	Shale with siderite mudstone nodules		7' 2"
30	Dark grey laminted shales with limestone nodules		7' 10"
29	Sulphur Band. Fissile black shale		6"

Zone of *Pleuroceras spinatum* 17'9"

Subzone of *Pleuroceras hawskerense* 2' 11"

28	Medium grey silty shales with 6" siderite mudstone nodules at middle		

Subzone of *Pleuroceras apyrenum* 14'10"

27	Main Seam, Top Block. Sideritic chamosite oolite		3' 2"
26	Middle Band. Siderite mudstone and shale		1' 8"
25	Main Seam, Bottom Block. Sideritic chamosite oolite		1' 9"
24	Blue Mottle. Sideritic shale with Rhizocorallium		1' 6"
23	Black Hard. Shale		1' 8"
22	Siderite mudstone 5"	*Pecten* Seam Top Unit	1' 11"
21	Chamositic shale 6"		
20	Siderite mudstone 6"		
19	Chamositic shale 6"		
18	Eston Shell Beds. Shelly chamosite siderite mudstone and chamositic shales		3' 2"

Zone of _Amaltheus margaritatus_ (pars.)

Subzone of _Amaltheus gibbosus_ 27'9"

17	Dark grey shale	2'	9"
16	_Two Foot Seam_. Spastolithic chamosite oolite		4"
15	Dark grey shale with bed of 2" siderite mudstone nodules at middle	10'	4"
14	_Raisdale Seam_. Oolitic siderite mudstone		9"
13	Laminated shales and silty shales	3'	3"
12	Dark grey shales passing up into medium shales	6'	2"
11	Bed of 2" siderite mudstone nodules		
10	Dark grey shale	4'	2"

Subzone of _Amaltheus subnodosus_ 22'2"

9	_Avicula Seam, Top Block_. Oolitic siderite mudstone	1'	6"
8	Shale		7"
7	_Avicula Seam, Bottom Block_. Oolitic siderite mudstone	1'	4"
6	Light grey silty shales with 6" siderite mudstone nodules	1'	10"
5	Laminated calcareous siltstone (_Entolium_)		7"
4	Light grey silty shales with siderite mudstone nodules	6'	3"
3	Medium to dark grey shales	4'	2"
2	Medium to light grey silty shales with siderite mudstone nodules	3'	7"

1	Medium grey shale	2' 4"

Subzone of <u>Amaltheus stokesi</u>

0 <u>Osmotherley Seam.</u> 4" nodules only

GRINKLE MINES (NZ 760177)

Zone of Dactylioceras tenuicostatum (pars.)

11	Shales with siderite mudstone nodules		
10	Medium grey silty shales with 5" siderite mudstone nodules at middle (horizon of Top Main Dogger)	4'	6"
9	Sulphur Band. Black fissile shale		5"

Zone of Pleuroceras spinatum

Subzone of Pleuroceras hawskerense 3' 8"

8	Medium grey silty shales with bed of 6" siderite mudstone nodules at middle underlain by 10" of light grey silty shale	3'	8"

Subzone of Pleuroceras apyrenum (pars.)

7	Main Seam, Top Block. Sideritic chamosite oolite	3'	5"
6	Ferruginous shale	1'	4"
5	Main Seam, Bottom Block. Oolitic siderite mudstone	2'	9"
4	Blue Mottle. Shaly siderite mudstone with Rhizocorallium	1'	6"
3	Black Hard. Shale	1'	8"
2	Pecten Seam, Top Unit, alternating siderite mudstones and chamositic shales, unfossiliferous	1'	10"
1	Eston Shell Beds Fossiliferous siderite mudstones and chamositic shales seen to	2'	8"

Subzone of <u>Amaltheus subnodosus</u> (pars.)

4	<u>Avicula Seam, Top Block</u>. Oolitic siderite mudstone			9"
3	Shale			9"
2	<u>Avicula Seam, Bottom Block.</u> Oolitic siderite mudstone		1'	6"
1	Light grey silty shales with siderite mudstone nodules especially at the top	seen to	6'	4"

KETTLENESS (NZ 832162)

Zone of Dactylioceras tenuicostatum (pars.)

48	Dark grey shale with six beds of siderite mudstone concretions.	8' 11"
47	Bed of 2" discrete calcite mudstone nodules.	
46	Dark grey shale	1' 2"
45	Laminated sideritic shale.	2"
44	Dark grey shale	1' 9"
43	Laminated sideritic shale	3"
42	Medium grey silty shale (P. hawskerense, belemnites wood)	1' 10"
41	Bed of 2" discrete calcite mudstone concretions (Pholadomya sp., growth position, Pinna sp., growth position, Pseudopecten)	
40	Medium grey silty shale with shell bed at base, (belemnites)	1' 6"
39	Sulphur Band. Dark grey shale laminated with light grey shale; pyritic with siderite mudstone nodules, (Arenicolites)	8"

Zone of Pleuroceras spinatum 25'7"

Subzone of Pleuroceras hawskerense 9'11"

38	Medium grey silty shale with siderite mudstone marbles. (Pleuroceras hawskerense, Protogramoceras bassanii, Tetrarhynchia tetrahedra, crinoid ossicles)	1' 0"

37	Tabular siderite mudstone concretions in double or treble bed, with prominent capping of 'beef' in places (Pholodomya, growth position, Pleuromya costata, growth position, P. hawskerense, Unicardium subglobosus, Tetrarhynchia tetrahedra)		9"
36	Light grey silty shale with 5" siderite mudstone concretions and rippled calcareous siltstone at the base	1'	11"
35	Medium grey silty shale	1'	1"
34	6" Bed of discrete siderite mudstone concretions		
33	Medium grey silty shale		10"
32	4" Bed of discrete siderite mudstone concretions		
31	Medium grey silty shale	1'	4"
30	3" Bed of discrete siderite mudstone concretions		
29	Medium grey silty shale	1'	4"
28	5" Bed of conjugate siderite mudstone concretions with capping of 'beef' in places		
27	Medium grey silty shale	1'	8"

Subzone of Pleuroceras apyrenum 15'8"

26	Main Seam - Top Block. Shelly oolitic siderite mudstone	1'	11"
25	Medium grey silty shale	2'	0"
24	Main Seam - Bottom Block. Shaly siderite mudstone with shelly lenses	3'	1"

23	*Blue Mottle*. Chamosite-siderite mudstone with *Rhizocorallium*					10"
22	*Black Hard*. Chamositic sideritic shale					1' 1"
21	Siderite mudstone	6"				
20	Sideritic shale	4"	Pecten Seam			
19	Siderite mudstone	4"				1' 7"
18	Sideritic shale	1"	Top Unit			
17	Siderite mudstone	4"				
16	Sideritic shale			1'4"		
15	Siderite mudstone			4"		
14	Shelly sideritic chamositic shale			5"		
13	Shelly siderite mudstone			4"		
12	Shelly sideritic chamositic shale			1"	Eston	
11	Shelly siderite mudstone			6"	Shell	5' 2"
10	Shelly sideritic chamositic shale			3"	Beds	
9	Shelly siderite mudstone			3"		
8	Shelly, pebbly, sideritic chamositic shale			5"		
7	Shelly siderite mudstone			5"		
6	Shelly sideritic chamositic shale (*Pseudopecten equivalvis*, *Ostrea*, *Gresslya*, belemnites, *Rhizocorallium*)			10"		

Zone of Amaltheus margaritatus

Subzone of Amaltheus gibbosus

5	Dark grey shale		1' 1"
4	Two Foot Seam. Shelly chamosite oolite and siderite mudstone		7"
3	Dark grey pyritic shale	(acc. to Howarth)	5' 0"
2	2" bed of conjugate siderite mudstone concretions		
1	Dark grey pyritic shale	(acc. to Howarth)	4' 0" seen

HAWSKER BOTTOMS (OV 953073)

Zone of Dactylioceras tenuicostatum

56	Dark grey shale with six beds of siderite mudstone nodules	8'	4"
55	Nodular calcite/siderite mudstone		2"
54	Dark grey shale	1'	3"
53	Sideritic shale with 3" siderite mudstone nodules		3"
52	Dark grey shale	1'	6"
51	Sideritic shale with occasional siderite mudstone nodules (Dactylioceras sp.)		3"
50	Medium grey silty shale	1'	9"
49	Nodular calcite siderite mudstone with shell bed at top (Pholadomya*, Pleuromya castata*, Pseudopecten equivalvis, Ostrea, belemnites)		3"
48	Medium grey silty shale withthin shell bed at base (belemnites)	1'	3"
47	Sulphur Band. Laminated dark to light grey pyritous shale (Arenicolites).		4"

Zone of Pleuroceras spinatum 35'0"

Subzone of Pleuroceras hawskerense 16'2"

46	Medium grey silty shale (P. hawskerense)	1'	1"
45	Nodular siderite mudstone with shell bed at top (P. hawskerense, Tetrarhynchia tetrahedra, crinoid ossicles, belemnites)		5"

44 Calcareous siltstone and light grey silty shale, strongly reworked by fauna. Lamination and ripple mark preserved at base. 1' 6"

43 Medium grey silty shales with discrete to conjugate siderite mudstone nodules

(vi) 7" nodules at 5'2" from base

(v) 6" nodules at 4!5" from base

(iv) 5" nodules at 3'5" from base 5' 11"

(iii) 6" nodules at 2'10" from base

(ii) 4" nodules at 2'2" from base

(i) 4" nodules at 1'8" from base

(*Pleuroceras hawskerense*, *Pleuromya costata**, *Unicardium subglobosum*, *Pholadomya**).

42 Highly nodular siderite mudstone in double bed with prominent 'beef' cappings in places (*P. hawskerense*, *Amauroceras ferrugineum*, *Pseudopecten equivalvis*, *Unicardium subglobosum*, *Pholadomya**). 8"

41 Medium grey silty shale becoming less silty towards base, with discrete to conjugate siderite mudstone nodules

(iii) 3" nodules 3'9"

(ii) 3" nodules 2'7" 6' 6"

(i) 4-5" nodules 2'3"

Subzone of Pleuroceras apyrenum 18'10"

40	Main Seam, Top Block			
	(iii) Silty sideritic shale with 4" mudstone nodules at top (Pleuroceras sp., Gresslya*, Pseudopecten, Pholadomya*, wood)	7"		
	(ii) Medium grey silty shale with 1" sideritic shale horizon at middle (wood)	8"	1'	9"
	(i) Silty sideritic shale with 4" siderite mudstone nodules at top	6"		
39	Medium grey silty shale	1'	1'	2"
38	Main Seam, Bottom Block			
	(iv) Silty sideritic shale with shelly siderite mudstone nodules	4"		
	(iii) Medium grey silty shale with occasional siderite mudstone nodules (P. hawskerense)	10"		
	(ii) Silty sideritic shale with 4" siderite mudstone nodules at top (P. apyrenum, Pholadomya*)	1'5"	3'	0"
	(i) Large conjugate siderite mudstone nodules (Pholadomya*)	5"		
37	Blue Mottle. Silty sideritic shale with shelly lenses (Pseudopecten, belemnites, Pentacrinus ossicles, wood, Rhizocorallium)		1'	4"
36	Medium grey silty shale		2'	0"

35	Silty sideritic shale with 6-7" conjugate siderite mudstone nodules (*Pseudopecten*)	7"		
34	Medium grey silty shale (*Rhizocorallium*)	4"	Pecten Seam Top Unit	2' 1"
33	Silty sideritic shale	5"		
32	Medium grey silty shale	4"		
31	Silty sideritic shale with discrete 3" siderite mudstone nodules (*Pseudopecten*, *Gresslya**, *Ostrea*, belemnites, wood, *Rhizocorallium*)	5"		
30	Medium grey silty shale	5"		
29	Silty sideritic shale (*Pseudopecten*, belemnites, wood, *Rhizocorallium*)	3"		
28	Nodular siderite mudstone (*Pseudopecten*, wood, *Rhizocorallium*)	6"		
27	Silty sideritic shale with shelly lenses (*Pseudopecten*, *Ostrea*, belemnites)	1'5"	Pecten Seam Eston Shell Beds	6'3"
26	Medium grey silty shale	1'3"		
25	Silty sideritic shale, shelly and pebbly (*Pseudopecten*, *Ostrea*, belemnites, *Rhizocorallium*)	7"		
24	Medium grey silty shale (Pseudopecten)	10"		
23	Silty sideritic shale	5"		
22	Medium grey silty shale, pebbly with *Rhizocorallium*	7"		

21	Oolitic siderite mudstone	7"		
20	Silty pyritic sideritic shale (*Pseudopecten*, belemnites)	4"	*Pecten Seam*	
19	Pebbly oolitic siderite mudstone, with spastolithic chamosite oolite above. (*Pleuroceras solare*, *A. margaritatus*, *Gresslya*, *Ostrea*, *Pseudopecten*)	4"	*Grosmont Unit*	1' 3"

Zone of *Amaltheus margaritatus* (pars.)

Subzone of *Amaltheus gibbosus* 20'9"

18	Dark grey pyritic shale (wood)	1' 6"
17	*Raisdale Seam*. Oolitic siderite mudstone and spastolithic chamosite oolite	3"
16	Dark grey shale and very light grey silt in graded laminations, with longitudinal current scours and other sedimentary structures. Large lenticular siderite mudstone nodules 6-8" in top 3'0" (*Pseudopecten*, *Ostrea*)	3' 10"
15	Bed of 3" discrete calcite mudstone nodules (*A. margaritatus*)	
14	Graded laminated siltstone and shale as above with longitudinal current scours becoming less silty at base	2' 10"
13	Large lenticular siderite mudstone nodules 6-10"	
12	Dark to medium grey pyritic shale with occasional silty laminations at top, 3" calcite mudstone nodules $^1/_3$ way up. (Pentacrinus).	4' 2"

11	Large siderite mudstone nodules in double bed 6".		
10	Dark grey pyritic shale with scattered 2" calcite mudstone nodules at base (<u>A. gibbosus</u>, <u>Pentacrinus</u>)	3'	8"
9	Double bed of large siderite mudstone nodules		
8	Dark grey pyritic shale with scattered 3" calcite mudstone nodules at top.	4'	6"

Subzone of <u>Amaltheus subnodosus</u> 17'8"

7	<u>Avicula Seam</u>. Shaly spastolithic chamosite oolite, and sideritic shale with 3" siderite mudstone nodules, pebble and shell beds at top and bottom.		9"
6	Nodular siderite mudstone bed		6"
5	Medium grey silty shales with siderite mudstone nodules (<u>Gresslya</u>*)	3'	0"
4	Medium to dark grey shales (<u>A. margaritatus</u>)	6'	3"
3	Bed of 2" limestone nodules		
2	Dark grey shale	2'	1"
1	Medium grey silty shales with siderite mudstone nodules (<u>A. margaritatus</u>, <u>A. subnodosus</u>, <u>Modiola scalprum</u>)		

Subzone of <u>Amaltheus stokesi</u> (pars.)

0	<u>Osmotherley Seam</u>. Oolitic siderite mudstones		3"

* Indicates fossils in position of life.

HOWDALE GILL (OV 949023)

Zone of Dactylioceras tenuicostatum

17	Sulphur Band. Black fissile shale		

Zone of Pleuroceras spinatum 37'7"

Subzone of Pleuroceras hawskerense 17'7"

16	Medium grey silty shale	1'	2"
15	Contimous bed of siderite mudstone concretions		4"
14	Calcareous siltstone	1'	6"
13	Medium grey silty shales with siderite mudstone nodules	7'	0"
12	Bed of continuous siderite mudstone concretions with cone-in-cone at top		9"
11	Medium grey silty shales with siderite mudstone nodules	6'	10"

Subzone of Pleuroceras apyrenum 20'0"

10	Main Seam, Top Block. Ferruginous shale with siderite mudstone nodules	1'	4"
9	Shale	2'	0"
8	Main Seam, Bottom Block. Ferruginous shale with siderite mudstone nodulse	2'	10"
7	Shale	3'	0"
6	Pecten Seam, Top Unit. Ferruginous shale with siderite mudstone nodules top and bottom	1'	4"
5	Eston Shell Beds. Ferruginous shelly shales with siderite mudstone nodules	7'	8"
4	Pecten Seam, Grosmont Unit Shaly siderite mudstone	1'	10"

Zone of _Amaltheus margaritatus_ (pars.)

Subzone of _Amaltheus gibbosus_ (pars.)

3.	Dark grey shale	2' 3"
2.	_Raisdale Seam._ Siderite mudstone	10"
1.	Laminated silty shale with current scours	

IBURNDALE (NZ 875061)

Subzone of *Pleuroceras apyrenum* (pars.)

8	Medium grey silty shales	
7	Bed of 6" siderite mudstone nodules	
6	Medium grey silty shales	6' 0"
5	Pecten Seam, Grosmont Unit. Sideritic mudstones with shale partings	2' 6"

Zone of *Amaltheus margaritatus* (pars.)

Subzone of *Amaltheus gibbosus* (pars.)

4	Dark grey shale	2"
3	Two Foot Seam. Oolitic siderite mudstone	9"
2	Dark grey shale with bed of 5" siderite mudstone nodules	5' 11"
1	Raisdale Seam. Oolitic siderite mudstone	10"

GROSMONT (NZ 829052-829058)

Zone of Dactylioceras tenuicostatum (pars.)

50	Shale with siderite mudstone nodules		
49	Medium grey shale with row of limestone nodules	3'	3"
48	Sulphur Band. Black fissile shale, sideritic at top		9"

Zone of Pleuroceras spinatum 32'10"

Subzone of Pleuroceras hawskerense 13'11"

47	Dark grey shale	1'	9"
46	Nodular siderite mudstone bed, with cone-in-cone structure at top		8"
45	Light grey silty shale	2'	9"
44	Bed of 3" siderite mudstone nodules		
43	Medium grey silty shales passing upwards	1'	10"
42	Bed of 2" siderite mudstone nodules		
41	Medium grey silty shales	1'	5"
40	Bed of 3" siderite mudstone nodules		
39	Medium grey silty shales	1'	2"
38	Bed of 3" siderite mustone nodules		
37	Medium grey silty shale		5"
36	Nodular siderite mudstone bed with cone-in-cone structure at top		10"
35	Medium grey silty shale	3'	1"

Subzone of <u>Pleuroceras apyrenum</u> 18'11"

34	<u>Main Seam, Top Block.</u> Shelly siderite mudstone				11"
33	Medium grey ferruginous shales			3'	8"
32	Bed of 6" siderite mudstone concretions				
31	Medium grey ferruginous shales with shelly lenses replaced by siderite nodules			4'	3"
30	Bed of 5" siderite mudstone concretions				
29	Medium grey ferruginous shales			1'	11"
28	Bed of 6" siderite mudstone concretions				
27	Medium grey ferruginous shales			1'	1"
26	Bed of 5" siderite mudstone concretions				
25	Medium grey ferruginous shales			3'	0"
24	Shelly siderite mudstone	10"	<u>Pecten</u>		
23	Shelly chamositic shale and siderite mudstone	1' 6"	Seam		
22	Shelly chamosite-siderite mudstone	6"	Grosmont	4'	2"
21	Shelly siderite mudstone	1"	Unit		
20	Chamositic shale	3"			

Zone of <u>Amaltheus margaritatus</u> (pars.)

Subzone of <u>Amaltheus gibbosus</u> 29'10"

19	Dark grey shale	3'	3'	7"
18	<u>Two Foot Seam</u>. Oolitic siderite mudstone			10"
17	Dark grey shale		3'	7"
16	Bed of 4" siderite mudstone nodules			

15	Dark grey shale	4'	0"
14	Raisdale Seam. Oolitic siderite mudstone		4"
13	Medium grey shales passing up into laminated silty shales with current scours	5'	9"
12	Dark grey shales passing up into medium grey shales	8'	2"
11	Bed of 2" siderite mudstone nodules		
10	Dark grey shale	3'	7"

Subzone of Amaltheus subnodosus 25'10"

9	Avicula Seam, Top Block. Oolitic siderite mudstone	1'	3"
8	Shale		4"
7	Avicula Seam, Bottom Block. Oolitic siderite mudstone shelly and pebbly at base	2'	7"
6	Light grey silty shales	1'	9"
5	Hard laminated siltstone with 6" siderite mudstone nodules		9"
4	Medium grey silty shales with siderite mudstone nodules	6'	0"
3	Dark grey shales	5'	8"
2	Medium grey silty shales with siderite mudstone nodules	4'	11"
1	Medium grey silty shales	2'	7"

Subzone of Amaltheus stokesi (pars.)

0	Osmotherley Seam. Oolitic siderite mudstone		5"

WEST ARNECLIFF WOODS/GLAISDALE (NZ 776042)

Zone of Dactylioceras tenuicostatum

23	Shales with siderite mudstone nodules		
22	Medium grey silty shales	3'	5"
21	Sulphur Band. Black fissile shale		9"

Zone of Pleuroceras spinatum 21'5"

Subzone of Pleuroceras hawskerense 7'7"

20	Medium grey silty shale	1'	4"
19	Composite bed of siderite mudstone nodules		10"
18	Light grey silty shales with small siderite nodules	1'	8"
17	Medium grey silty shales with 5" siderite mudstone near middle	4'	5"

Subzone of Pleuroceras apyrenum 13'10"

16	Main Seam, Top Block Shaly siderite mudstone		11"
15	Medium grey silty shales	2'	10"
14	Bed of 9" siderite mudstone nodules		
13	Medium grey silty shales	4'	1"
12	Bed of 6" siderite mudstone nodules		
11	Medium grey silty shales	2'	6"
10	Bed of 6" siderite mudstone nodules		
9	Medium grey silty shales (shelly)	1'	4"
8	Pecten Seam, Grosmont Unit. Siderite mudstone with chamositic shales	2'	2"

Zone of Amaltheus margaritatus (pars.)

Subzone of Amaltheus gibbosus 30'7"

7	Dark grey shale	1'	11"
6	Two Foot Seam. Oolitic siderite mudstone	1'	2"
5 *	Shale	6'	0"
4 *	Raisdale Seam - not recorded		
3 *	Hard shale, slaty and gritty	6'	0"
2 *	Shale	15'	6"

Subzone of Amaltheus subnodosus (pars.)

1 *	Avicula Seam. Ironstone and shale	5'	0"

* Details supplemented from Fox-Strangways et al. (1885, p. 11).

GREAT FRYUP DALE (NZ 717022)

Zone of _Dactylioceras tenuicostatum_ (pars.)

13	_Sulphur Band_. Black fissile shale	9"

Zone of _Pleuroceras spinatum_ 15'5"

Subzone of _Pleuroceras hawskerense_ 7' 1"

12	Medium grey shale slightly fissile	2' 11"
11	Light grey silty shale with bed of 5" siderite mudstone nodules at middle	2' 7"
10	Medium grey silty shales	1' 7"

Subzone of _Pleuroceras apyrenum_ 8'4"

9	_Main Seam, Top Block_. Shaly siderite mudstone	4"
8	Medium grey silty shales	2' 3"
7	Bed of 7" siderite mudstone nodules	
6	Medium grey silty shales	3' 1"
5	Bed of 9" siderite mudstone nodules	
4	Medium grey silty shales (shelly)	2' 6"
3	_Pecten Seam, Grosmont Unit_. Siderite mudstone and chamositic shale	2"

Zone of _Amaltheus margaritatus_ (pars.)

Subzone of _Amaltheus gibbosus_ (pars.)

2	Dark grey shale	5"
1	_Two Foot Seam_. Sideritic chamosite oolite	seen to 1' 10"

ROSEDALE HEAD (NZ 698002)

Subzone of Pleuroceras apyrenum (pars.)

20	Medium grey silty shales		
19	Bed of 5" siderite mudstone nodules		
18	Medium grey silty shales	3'	3"
17	Bed of 4" siderite mudstone nodules		
16	Medium grey silty shales (shelly)	1'	9"
15	Pecten Seam, Grosmont Unit. Pebbly sideritic shale		3"

Zone of Amaltheus margaritatus (pars.)

Subzone of Amaltheus gibbosus 26'1"

14	Two Foot Seam (truncated) shelly oolitic siderite mudstone	1'	4"
13	Dark grey shales with two beds of 3" siderite mudstone nodules	6'	0"
12	Raisdale Seam. Siderite mudstone		7"
11	Laminated silty shales with lenticular siderite mudstone nodules	5'	6"
10	Dark to medium grey silty shales	8'	10"
9	Bed of 4" siderite mudstone nodules		
8	Dark grey shales	3'	9"

Subzone of Amaltheus subnodosus (pars.)

7	Avicula Seam. Shaly siderite mudstone and shale	1'	11"
6	Light grey silty shale with siderite mudstone nodules		6"

5	Laminated siltstone			6"
4	Light grey silty shales with siderite mudstone nodules	seen to	1'	6"
3	Medium to dark grey shales		?	
2	Light grey silty shales with siderite mudstone nodules		?	
1	Medium grey shales		4'	0"

Subzone of Amaltheus stokesi (pars.)

0	Osmotherley Seam. Siderite mudstone	7"

FARNDALE HEAD (NZ 632008)

Subzone of Pleuroceras apyrenum (pars.)

7	Medium grey silty shale	seen to	1' 8"
6	Pecten Seam, Grosmont Unit. Shaly siderite mudstone		11"

Zone of Amaltheus margaritatus

Subzone of Amaltheus gibbosus

5	Dark grey shale	6"
4	Two Foot Seam. Oolitic siderite mudstone	1' 10"
3	Dark grey shale with two beds of siderite mudstone nodules	7' 3"
2	Raisdale Seam. Siderite mudstone	7"
1	Laminated silty shales with lenticular siderite mudstone nodules	

WESTERDALE (NZ 672069)

Subzone of Amaltheus gibbosus (pars.)

12	Bed of 4" siderite mudstone nodules		
11	Dark grey shales	4'	6"
10	Raisdale Seam. Siderite mudstone		10"
9	Dark grey silty shales passing up into laminated silty shales with siderite mudstone lenses seen to	9'	10"
8	Bed of 2" siderite mudstone nodules		
7	Dark grey shale	4'	3"

Subzone of Amaltheus subnodosus 22'10"

6	Avicula Seam. Shales with two thin beds of pebbly siderite mudstone	1'	9"
5	Light grey silty shale with siderite mudstone nodules	1'	5"
4	Tabular siderite mudstone concretions		4"
3	Medium grey silty shales with siderite mudstone nodules	6'	1"
2	Dark grey shale	6'	5"
1	Medium grey silty shales with siderite mudstone nodules	about 6'10"	

Subzone of Amaltheus stokesi (pars.)

0	Osmotherley Seam. Siderite mudstone		4"

BRANSDALE (SE 621952)

Zone of Dactylioceras tenuicostatum

11	Sulphur Band. Black fissile shale (recorded by Tate and Blake, 1876, p. 150 as "Jet Rock (slipped)"	1'	7"

Zone of Pleuroceras spinatum 8'11"

Subzone of Pleuroceras hawskerense 6"

10	Medium grey micaceous shale with 4" siderite mustone nodules		6"

Subzone of Pleuroceras apyrenum 8' 5"

9	Main Seam, Top Block. Oolitic siderite mustones and shales	2'	5"
8	Medium grey silty shale with bed of 6" siderite mudstone nodules 3'4" from base	5'	0"
7	Pecten Seam, Grosmont Unit Shaly siderite mudstone	1'	0"

Zone of Amaltheus margaritatus (pars.)

Subzone of Amaltheus gibbosus

6	Dark grey shale	2'	5"
5	Two Foot Seam. Chamosite oolite with siderite mustone	2'	9"
4	Dark grey shales with siderite mudstone nodules at top	?	
3	Bed of 4" siderite mudstone nodules		
2	Dark grey shales	5'	8"
1	Raisdale Seam. Siderite mudstone		8"

BOTTON HEAD (GREENHOW MOOR) (NZ 596023)

Zone of Dactylioceras tenuicostatum (pars.)

24	Shale with siderite mudstone nodules (Dactylioceras)		
23	Medium grey silty shales with siderite mudstone nodules contain Gibbirhychia tiltonensis	4'	2"
22	Top Main Dogger. Siderite mudstone (Pleuromya costata)		8"
21	Medium grey silty shale		7"
20	Sulphur Band. Black pyritic shale interlaminted with pyritic oolite	1'	0"

Zone of Pleuroceras spinatum 6'6"

Subzone of Pleuroceras apyrenum 6'6"

19	Main Seam, Top Block. Oolitic siderite mudstone	1'	4"
18	Medium grey silty shale with bed of 6" siderite mudstone nodules at middle	3'	0"
17	Pecten Beds. Shelly chamosite-siderite mudstones and chamositic shales	2'	2"

Zone of Amaltheus margaritatus (pars.)

Subzone of Amaltheus gibbosus 24' 5"

16	Dark grey shale		11"
15	Two Foot Seam. Oolitic siderite mudstone	1'	7"
14	Dark grey shale with 4" siderite mudstone nodules at middle	5'	8"

13	<u>Raisdale Seam</u>. Oōlitic siderite mudstone	7"
12	Laminated shales and siltstones with large lenticular siderite mudstone nodules	5' 1"
11	Dark grey shales passing up into medium grey silty shales	7' 2"
10	Bed of 4" siderite mudstone nodules	
9	Dark grey shales	3' 5"

Subzone of <u>Amaltheus subnodosus</u> 23'10"

8	<u>Avicūla Seam.</u> Shaly pyritic siderite mudstone	10"
7	Light grey silty shales with large tabular siderite mudstone concretions at base	4' 6"
6	Laminated silstone	6"
5	Medium to light grey silty shales with siderite mudstone nodules	4' 10"
4	Dark grey shale	5' 7"
3	Medium grey silty shales with siderite mudstone nodules	4' 7"
2	Laminated siltstone	3"
1	Medium grey shale	2' 9"

Subzone of <u>Amaltheus stokesi</u> (pars.)

0	<u>Osmotherley Seam</u>. Oolitic siderite mudstone	7"

HARTON GILL-RAISDALE (SE 545992)

Zone of Dactylioceras tenuicostatum (pars.)

18	Shales with siderite mudstone nodules	3' 3"
17	Top Main Dogger. Oolitic siderite mudstone with ferruginous shale	2' 4"
16	Sulphur Band. Fissile black shale with pyritous oolite at base	1' 7"

Zone of Pleuroceras spinatum 4'4"

Subzone of Pleuroceras apyrenum 4'4"

15	Main Seam, Top Block. Oolitic siderite mudstone	1' 10"
14	Grey ferruginous shale	1' 1"
13	Pecten Seam. Siderite mudstone with chamositic shales	1' 5"

Zone of Amaltheus margaritatus (pars.)

Subzone of Amaltheus gibbosus 21'5"

12	Two Foot Seam. Oolitic siderite mudstone	1' 2"
11	Dark grey shales with two beds of siderite mudstone nodules	6' 11"
10	Raisdale Seam. Sideritic chamosite oolite	1'4"
9	Laminated grey silty shales with lenticular siderite mudstone nodules	3' 4"
8	Dark grey shales passing upwards into medium grey silty shales	8' 8"

Subzone of Amaltheus subnodosus 25'9"

7	Avicula Seam. Shelly oolitic siderite mudstone	1'	4"
6	Light grey silty shale with large siderite mudstone nodules	3'	9"
5	Laminated siltstone	1'	0"
4	Light grey silty shales with siderite mudstone nodules	2'	6"
3	Dark to medium grey silty shales	14'	0"
2	Bed of 2" siderite mudstone nodules		
1	Medium grey silty shale	3'	2"

Subzone of Amaltheus stokei (pars.)

0	Osmotherley Seam. Oolitic siderite mudstone		6"

SCUGDALE HEAD (SE 526992)

Zone of Dactylioceras tenuicostatum (pars.)

15	Shales with siderite mudstone nodules	3'	5"
14	Top Main Dogger. Siderite mudstone with ferruginous shale	3'	0"
13	Sulphur Band. Black fissile shale with pyritous oolite at base	1'	5"

Zone of Pleuroceras spinatum 3' 2"

Subzone of Pleuroceras apyrenum 3'2"

12	Main Seam, Top Block. Oolitic siderite mudstone	2'	0"
11	Ferruginous shale		5"
10	Pecten Seam. Siderite mudstone		9"

Zone of Amaltheus margaritatus (pars.)

Subzone of Amaltheus gibbosus 20'10"

9	Two Foot Seam (truncated) oolitic siderite mudstone	1'	0"
8	Dark grey shales with two beds of siderite mudstone nodules	6'	1"
7	Raisdale Seam. Sideritic chamosite oolite	1'	6"
6	Laminated grey silty shales with lenticular siderite mudstone nodules	4'	8"
5	Dark grey shales passing up into medium grey silty shales	7'	7"

Subzone of <u>Amaltheus subnodosus</u> (pars.)

4	<u>Avicula Seam</u>. Shelly siderite mudstone	1'	2"
3	Light grey silty shales with large siderite mudstone nodules	3'	9"
2	Laminated siltstone	1'	1"
1	Light grey silty shales with siderite mudstone nodules seen to	7'	6"

COD BECK, OSMOTHERLEY (SE 464965)

Zone of Dactylioceras tenuicostatum (pars.)

12	Shales with Dactylioceras	
11	Top Main Dogger Ferruginous shale with siderite mudstone beds and nodules	4' 1"
10	Sulphur Band. Black fissile shale	2' 0"

Zone of Pleuroceras spinatum 2'2"

Subzone of Pleuroceras apyrenum 2'2"

9	Main Seam, Top Block. Oolitic siderite mudstone	1' 10"
8	Pecten Seam. Pebbly chamositic shale	4"

Zone of Amaltheus margaritatus (pars.)

Subzone of Amaltheus gibbosus 14'2"

7	Dark grey shale	1' 4"
6	Raisdale Seam. Oolitic siderite mudstone	11"
5	Dark grey shales passing up into medium grey shales and then laminated silty shales with lenticular siderite mudstone nodules.	11' 11"

Subzone of Amaltheus subnodosus 19'9"

4	Avicula Seam. Siderite mudstone pebbly at base	1' 3"
3	Light grey silty shales with 7" tabular siderite mudstone concretions	11"
2	Laminated siltstone	5"

1	Dark to medium grey silty shales with siderite mudstone nodules	17' 2"

Subzone of _Amaltheus stokesi_ (pars.)

0	_Osmotherley Seam_.	1' 2"

DIMMINGDALE BOREHOLE (NZ 688129)

(Of the three boreholes put down in the area of Moorsholme - see Lamplugh et al. (1920), the only one which is at all comprehensible is the Dimmingdale Borehole which is interpreted as follows:-)

Zone of Pleuroceras spinatum

depth 743 Ft. Subzone of Pleuroceras apyrenum 20'11"

18	Ironstone and shale	(Main Seam, Top Block)	3' 0"
17	Shale		2' 5"
16	Ironstone Inferiorn ironstone	(Main Seam, Bottom Block)	1' 6"
15	Shale		4' 6"
14	Inferior ironstone 3'6" Dogger 7"	Pecten Seam Eston Shell Beds	4' 1"
13	Shale		3"
12	Blue Shale		2"
11=	Ironstone (good) 3'0" Inferior ironstone 2'0"	Pecten Seam Grosmont Unit	5' 0"

Zone of Amaltheus margaritatus

Subzone of Amaltheus gibbosus 32'4"

10	Shale		2'2"
9	Ironstone (good)	(TWO FOOT SEAM)	2' 0"
8	Shale		4' 1"

7	Ironstone and shale (Raisdale Seam)	7"
6	Grey sandstone with shale ribs	2' 3"
5	Grey sandy shale with sandstone ribs	3' 8"
4	Dark grey sandy shale	17' 7"

Subzone of *Amaltheus subnodosus*

3	Ironstone and shale (Avicula Seam)	1' 0"
2	Grey sandstone	7' 0"
1	Dark grey sandy shale (*subnodosus* beds and part of *stokesi* beds)	33' 6"

AYTON BANK MINE (NZ 588110)

Zone of Dactylioceras tenuicostatum (pars.)

13	Top Main Dogger. Shaly siderite mudstone	2'	8"
12	Sulphur Band. Laminated siderite mudstone with pyritous oolite at base		11"

Zone of Pleuroceras spinatum 12'4"

Subzone of Pleuroceras apyrenum 12'4"

11	Main Seam, Top Block. Sideritic chamosite oolite	2'	7"
10	Middle Band. Chamositic shale and siderite mudstone below	2'	0"
9	Main Seam, Bottom Block. Oolitic siderite mudstone	1'	2"
8	Blue Mottle and Black Hard. Chamositic sideritic shale with Rhizocorallium	1'	8"
7	Eston Shell Beds. Chamositic shales with rhynchonellids		5"
6	Grosmont Pecten Unit. Alternating siderite mudstones and chamositic shales	4'	8"

Zone of Amaltheus margaritatus (pars.)

Subzone of Amaltheus gibbosus (pars.)

5	Dark grey shale	1'	0"
4	Two Foot Seam. Sideritic chamosite oolite	?	
3	Dark grey shale	?	
2	Raisdale Seam. Oolitic siderite mudstone		8"
1	Laminated silty shales		

AYTON MINE (NZ 584104)

Zone of Dactylioceras tenuicostatum (pars.)

16	Shales with siderite mudstone nodules	7'	7"
15	Laminated shales with small limestone concretions	5'	0"
14	Top Main Dogger. Siderite mudstones and chamositic shales, *G. tiltonensis*	2'	4"
13	Sulphur Band. Black fissile shale partly replaced by siderite mudstone, pyritous at base (*Arenicolites*)	1'	1"

Zone of *Pleuroceras spinatum* 11'6"

Subzone of *Pleuroceras apyrenum* 11'6"

12	Main Seam, Top Block. Sideritic chamosite oolite	2'	7"
11	Middle Band. Chamositic shale and siderite mudstone below	1'	8"
10	Main Seam, Bottom Block. Sideritic chamosite oolite	1'	3"
9	Blue Mottle. Chamositic shale		10"
8	Black Hard. Shale		10"
7	Eston Shell Beds. Shelly chamositic shales with abundant rhynchonellids		10"
6.	Grosmont Pecten Unit. Alternating shelly siderite mudstones and chamositic shales	3'	6"

Zone of *Amaltheus margaritatus* (pars.)

Subzone of *Amaltheus gibbosus*

5	Dark grey shale	11"
4	Two Foot Seam. Sideritic chamosite oolite	1' 10"
3	Dark grey shale	?
2	Raisdale Seam. Oolitic siderite mudstone	8"
1	Laminated silty shales	

HUTTON LOWCROSS MINES (NZ 605134)

Zone of _Dactylioceras tenuicostatum_ (pars.)

13	_Top Main Dogger_. Oolitic siderite mudstone	2'	5"
12	_Sulphur Band_. Pyritous oolite and siderite mudstone		8"

Zone of _Pleuroceras spinatum_ 15'10"

Subzone of _Pleuroceras apyrenum_ 15'10"

11	_Main Seam, Top Block_. Sideritic chamosite oolite	3'	5"
10	_Middle Band_. Chamositic shale and siderite mudstone below	1'	9"
9	_Main Seam, Bottom Block_. Sideritic chamosite oolite	1'	4"
8	_Blue Mottle and Black Hard_. Chamositic shale with _Rhizocorallium_	2'	7"
7	_Eston Shell Beds_. Sideritic chamositic shales with rhynchonellids, pebbly at base		10"
6	_Grosmont Pecten Unit_. Shelly siderite mudstones alternating with chamositic shales	5'	11"

Zone of _Amaltheus margaritatus_ (pars.)

Subzone of _Amaltheus gibbosus_ (pars.)

5	Dark grey shale	2'	8"
4	_Two Foot Seam_. Oolitic siderite mudstone	2'	8"
3	Dark grey shale with bed of 2" siderite mudstone nodules at middle	4'	7"

2	Raisdale Seam. Oolitic siderite mudstone	8½"
1	Laminated silty shales	

WATERFALL GILL (NZ 635159-632165)

Zone of Pleuroceras spinatum

Subzone of Pleuroceras apyrenum 16'5"

24	Main Seam, Top Block. Sideritic chamosite oolite		2' 9"
23	Middle Band. Chamositic shale and siderite mudstone		2' 0"
22	Main Seam, Bottom Block. Sideritic chamosite oolite		2' 6"
21	Blue Mottle. Chamositic shale with Rhizocorallium		1' 0"
20	Black Hard Shale		1' 10"
19	Ferruginous shale with impersistant siderite mudstone nodules	Pecten Seam Top Unit	8"
18	Eston Shell Beds. Fossiliferous chamositic shells with rhynchonellids		10"
17	Ferruginous shales 10"	Pecten Seam Grosmont Unit	4' 10"
16	Shelly siderite mudstones with shaly partings 3' 6"		
15	Shelly chamositic shale 6"		

Zone of Amaltheus margaritatus (pars.)

Subzone of Amaltheus gibbosus 35'0"

14	Dark grey shale	4' 11"
13 *	Two Foot Seam. Oolitic siderite mudstone	2' 6"
12 *	Dark grey shale	6' 0"
11	Raisdale Seam. Spastolithic oolite	2"
10	Laminated grey silty shales	5' 4"

9	Dark grey shales passing upwards into medium grey silty shales	9'	9"
8	Bed of 2" siderite mudstone nodules		
7	Dark grey shales	4'	6"
6	Bed of 3" siderite mudstone nodules		
5	Dark grey shales	2'	0"
	Subzone of Amaltheus subnodosus (pars.)		
4	Avicula Seam. Oolitic siderite mudstone	1'	1"
3	Light grey silty shales with 5" siderite mudstone nodules	2'	9"
2	Laminated siltstone		5"
1	Light grey silty shales with siderite mudstone nodules seen to	3'	8"

* Details of section obscure and therefore supplemented from Barrow(1888).

CLIFF RIGG (NZ 575117)

Zone of *Dactylioceras tenuicostatum* (pars.)

43	Shale with siderite mudstone nodules (*Dactylioceras*)	9' 0"
42	Bed of 3" shelly siderite mudstone nodules (*Gibbirhynchia tiltonensis*, *Astarte*, etc.)	
41	Medium grey silty shales	5' 11"
40	*Top Main Dogger*. Sideritic-chamosite mudstones with scattered ooliths (G. tiltonensis)	3' 0"
39	*Sulphur Band*. Laminated siderite mudstone with pyritous oolite (Arenicolites)	

Zone of *Pleuroceras spinatum* 11'9"

Subzone of *Pleuroceras apyrenum* 11'9"

38	*Main Seam, Top Block*. Sideritic chamosite oolite	3' 2"
37	*Middle Band*. Sideritic chamosite shale underlain by siderite mudstone	1' 1"
36	*Main Seam, Bottom Block*. Sideritic chamosite oolite	1' 0"
35	*Blue Mottle*. Green chamositic shale with *Rhizocorallium*	7"
34	*Black Hard*. Dark green black shale	1' 0"
33	*Eston Shell Beds*. Chamositic shale with abundant rhynchonellids and belemnites	8"

32	Shelly siderite mudstone	7"			
31	Shelly chamositic shale	5"			
30	Shelly siderite mudstone	7"			
29	Shelly chamositic shale	8"	Pecten Seam		
28	Shelly siderite mudstone	5"	Grosmont	4'	6"
27	Very shelly chamositic shale	3"	Unit		
26	Shelly siderite mudstone	7"			
25	Very shelly chamositic shale	10"			

Zone of Amaltheus margaritatus (pars.)

Subzone of Amaltheus gibbosus 31'7"

24	Dark grey shale		10"
23	Two Foot Seam. Chamosite oolite with siderite mudstone lenses, shelly in places	2'	1"
22	Dark grey shale	2'	5"
21	Bed of 2" siderite mudstone nodules		
20	Dark grey shale	2'	10"
19	Raisdale Seam. Shelly oolitic siderite mudstone	1'	4"
18	Medium to light grey laminated silty shales	5'	7"
17	Medium to dark grey shales	16'	6"

Subzone of Amaltheus subnodosus 25'11"

16	Avicula Seam. Siderite mudstone, pebbly at top		9"
15	Light grey silty shales		8"
14	Hard sideritic laminated siltstone (Entolium)		11"

13	Light grey silty shales	1' 9"
12	Bed of 3" siderite mudstone nodules	
11	Light grey silty shales	5"
10	Bed of 3" siderite mudstone nodules	
9	Light grey silty shales	1' 2"
8	Bed of 3" siderite mudstone nodules	
7	Medium grey silty shales passing down into dark grey shales	10' 4"
6	Bed of 2" siderite mudstone nodules	
5	Medium grey silty shales	1' 8"
4	Bed of 5" siderite mudstone nodules	
3	Light grey silty shale	2' 1"
2	Laminated calcareous siltstone	4"
1	Dark grey shale passing up into light grey shale	5' 10"

Subzone of _Amaltheus stokesi_ (pars.)

0	_Osmotherley Seam_. Siderite mudstone	5"

SKELTON BECK-HOB HILL (NZ 655201-658201)

Zone of Dactylioceras tenuicostatum (pars.)

36	Shale with siderite mudstone nodules			9' 0"
35	Shale with small limestone nodules			6' 9"
34	Top Main Dogger. Siderite mudstone with scattered white ooliths. Gibbirhynchia tiltonensis			1' 10"
33	Sulphur Band. Very badly weathered			5"

Zone of Pleuroceras spinatum 12'5"

Subzone of Pleuroceras apyrenum 12'5"

32	Main Seam. Shelly intraclastic oolite with bright green chamosite matrix, crossbedded near top.			8' 4"
31	Black Hard. Shale			1' 8"
30	Shaly siderite mudstone	4"	Top Unit Pecten Seam	1' 2"
29	Shale	4"		
28	Shaly siderite mudstone	4"		
27	Shale	2"		
26	Eston Shell Beds. Shelly chamositic shale with abundant rhynchonellids			1' 3"

Zone of Amaltheus margaritatus (pars.)

Subzone of Amaltheus gibbosus 34'4"

25	Dark grey shale			6' 6"
24	Two Foot Seam. Oolitic siderite mudstone			2' 7"

23	Dark grey shale	5' 0"
22	Bed of 2" siderite mudstone nodules	
21	Dark grey shale	3' 6"
20	Raisdale Seam. Oolitic siderite mudstone	6"
19	Dark grey shales passing up into laminated silty shales	10' 8"
18	Bed of 3" siderite mudstone nodules	
17	Dark grey shales	4' 6"
16	Bed of 4" siderite mudstone nodules	
15	Dark grey shale	1' 1"

Subzone of Amaltheus subnodosus 28'3"

14	AvicularSeam. Shaly siderite mudstone pebbly and shelly at base.	1' 3"
13	Light grey silty shales with large composite siderite mudstone nodules	1' 2"
12	Hard sideritic laminated siltstone, shelly at base (Entolium)	5"
11	Light grey silty shales	2' 2"
10	Bed of 3" siderite mudstone nodules	
9	Medium grey silty shales	1' 7"
8	Bed of 3" siderite mudstone nodules	
7	Medium grey silty shales	10"
6	Bed of 3" siderite mudstone nodules	

5	Medium to dark grey shales	12' 8"
4	Bed of 3" siderite mudstone nodules	
3	Light grey silty shales	1' 5"
2	Hard laminated siltstone	4"
1	Dark grey shales passing up into silty shales	6' 5"

Subzone of Amaltheus stokesi (pars.)

0	Osmotherley Seam. Siderite mudstone	9"

UPLEATHAM MINES (NZ 634205-639204)

Zone of Dactylioceras tenuicostatum

8	Top Main Dogger. Siderite mudstone	seen to	2'	2"
7	Sulphur Band. Weathered away			8"

Zone of Pleuroceras spinatum 12'8"

Subzone of Pleuroceras apyrenum 12'8"

6	Main Seam. Sideritic chamosite oolite with bright green chamosite matrix		8'	6"
5	Blue Mottle and Black Hard. Chamositic shale		2'	0"
4	Pecten Seam, Upper Unit. Siderite mudstone and shale		1'	2"
3	Eston Shell Beds. Chamositic shale with rhychonellids		1'	0"

Zone of Amaltheus margaritatus (pars.)

Subzone of Amaltheus gibbosus (pars.)

2	Dark grey shale		5'	6"
1	Two Foot Seam. Oolitic siderite mudstone		2'	1"

ESTON MINES (NZ 578190)

Zone of Pleuroceras spinatum 13'9"

Subzone of Pleuroceras apyrenum 13'9"

8	*Main Seam in one undivided block	11' 0"
7	Blue Mottle and Black Hard. Green chamosite mudstone	1' 8"
6	Eston Shell Beds. Chamositic shales, fossiliferous, with rhynchonellids.	1' 1"

Zone of Amaltheus margaritatus (pars.)

Subzone of Amaltheus gibbosus (pars.)

5	Dark grey shale	6' 1"
4	Two Foot Seam. Oolitic siderite mudstone	2' 6"
3	Dark grey shale	4' 3"
2	Raisdale Seam. Shelly siderite mudstone	1' 3"
1	Laminated silty shales	

*Section obscured and data supplemented from Barrow (1888).

NORMANBY MINES (NZ 551164)

Zone of _Pleuroceras spinatum_ 10' 7"

Subzone of _Pleuroceras apyrenum_ 10' 7"

5	_Main Seam_. Chamosite oolite with bright green matrix	8' 0"
4	_Blue Mottle and Black Hard_. Chamositic shale	2' 1"
3	_Eston Shell Beds_. Pebbly chamosite shale with rhynchonellids	6"

Zone of _Amaltheus margaritatus_ (pars.)

Subzone of _Amaltheus gibbosus_ (pars.)

2	Dark grey shales	6' 4"?
1	_Two Foot Seam_ Oolitic siderite mudstone	

APPENDIX II SIZE ANALYSIS

Many methods are available for the preparation of mechanical analyses, and while it is recognised that the nominal sizes derived by different methods are often sufficient for the description and interpretation of sediments, it is also known that the results are not directly comparable, and that it may be necessary to apply correction factors for the comparison of data. In particular corrections have been derived for the comparison of size analyses made under the microscope, the only method available for many indurated rocks, with analyses made on loose sediment. Since sieving is the most widely used method for loose sediments over the range of sizes most amenable to microscopic analysis, most recent corrections aim at converting thin section measures to equivalent sieve diameters.

According to Rosenfeld et al. (1953, p. 115) the discrepancy between frequency distributions made by sieving and thin section arise from several causes such as the effect of sectioning, the conversion of number frequencies into weight frequencies, grain shape, sorting, packing and orientation, the relationship between the nominal sieve opening and the absolute size, etc., all of which vary in importance from one rock to another. One approach to the problem lies in attempting to isolate the most important causes and deriving theoretical corrections for them. This was the solution attempted by Krumbein (1935) and by many later authors. It is reviewed and criticised by Rosenfeld et al. (1953) who point out the difficulty of assessing the contribution made by each separate discrepancy to the whole. They therefore recommend that an empirical factor, based on parallel analyses by sieve and thin section, be derived for each different study. Clearly this is not always feasible and Friedman (1958, 1962) therefore attempted a general empirical correction suitable for use with well sorted quartz sands of medium to coarse size. In the samples studied by Rosenfeld et al. (1953) and Friedman (1958, 1962) it was recognised that a linear relationship existed between the distributions made by sieve and thin section, which facilitated the construction of linear regression correlation curves ~~(fig.)~~. However, the two types of distribution are not necessarily related linearly as was shown by Krumbein's (1935) experiment on the effect of sectioning perfectly sorted lead shot ~~(fig.)~~. In such a case a mechanical analyses by thin section is meaningless without some kind of correction. This was precisely the situation with microscopic analyses made on ooliths in the present study ~~(fig.)~~.

In these circumstances Friedman's (1958, 1962) overall regression correlation line was unsatisfactory ~~(fig.)~~, nor was it possible to derive a special regression curve because of the difficulty of separating the ooliths from their groundmass for sieving. Therefore, recourse was made to Greenman's (1951) theoretical mathematical solution, an extension of Krumbein's method for correcting the moments of a thin section distribution. By this, long axis frequency distributions made in thin section are converted into long axis frequency distributions of the type prepared from loose grains under the binocular microscope. What is involved most importantly, therefore, is the effect of sectioning, while problems of number to weight frequency and of sieve calibration are by-passed. Although the results are not directly comparable with sieve size analyses, the method has the advantage of being applicable to a wider variety of clastic sediment than the individual empirical corrections. It is equally valid for spherical and approximately ellipsoidal grains (Greenman 1950) and satisfactory over a wide range of sorting.

Provision is made by Greenman (1953) for both arithmetic and logarithmic classes, with appropriate multipliers set up as tables. It was necessary to extend these tables for the present distributions. Both arithmetic and logarithmic classes were used, depending upon the degree of sorting in the original distributions; arithmetic classes with an interval of 0.05 mm. for oolitic rocks and logarithmic $\frac{1}{2}$ ϕ classes for the more poorly sorted intraclastic oolites.

It may be assumed that the resultant long axis frequency distributions are linearly related to sieve-size distributions ~~(fig.)~~ so that given the relevant sieve data a linear correlation regression curve could be constructed. Apparently little more is required than a correction to the mean.

APPENDIX III CHAMOSITES FROM THE CLEVELAND IRONSTONE FORMATION

CHAMOSITES FROM THE CLEVELAND IRONSTONE FORMATION

A. GENERAL

Dating from the earliest petrological investigations on the Cleveland Main Seam the presence of an iron silicate in the ores was recognised (Dick 1856, Sorby 1856, Stead 1910). Dick (op.cit. p. 95) states:- "The green colour of the ore seems to be due to a silicate containing peroxide and protoxide of iron, but this could not be exactly determined." Both Sorby (op.cit.) and Stead (op.cit.) reached similar conclusions believing this silicate to be a by-product of the sideritisation of limestone (page 234). The exact identification of the mineral remained uncertain, therefore, until Hallimond (1925) completed his survey on British bedded iron ores. Largely on chemical grounds he reached the conclusion that this green silicate was chamosite ('chamoisite' of Berthier 1820, from the Upper Jurassic of the Chamoson, Switzerland), identical with material described previously from Schmiedefeld, Thuringia (Zalinski 1904), Wabana, Newfoundland (Hayes 1915) and Raasay, Scotland (Lee 1920). Chemical analyses and X-ray measurements indicated that chamosite was allied to, and yet distinct from other minerals in the chlorite group, with which it was classified (Hallimond 1925, p. 26, Harvey and Bannister in Hallimond 1939).

More recent work carried out since 1945 and summarised by Brindley (p. 104-108 in Brown 1961) and Deer et al. (1962) has served to underline the ambiguous position of chamosite in relationship to the chlorites on the one hand and kaolinite on the other. Both 7Å and 14Å varieties have been described in natural occurrences, the 14Å type being a higher temperature polymorph of the 7Å type according to Nelson and Roy (1958); they propose the term septechamosite (syn. berthierine (Brown 1955)) for the latter in contradistinction to normal chamosite.

Even within the septechamosites considerable variation exists:-

(i) differences in layer stacking appear to give rise to both single layer orthogonal* and monoclinic unit cells which occur in mixtures in lateritic septechamosites (Brindley 1951 a,b).

(ii) variations in disorder corresponding with random displacements in the x direction, produce reflections of differing intensity and definition in the ironstone septechamosite (Youell 1955, 1958a).

According to Youell (1955, 1958b) these disordered forms are intermediate between the orthogonal and monoclinic types and also symptomatic of isomorphous replacement of iron and aluminium over a wide range of compositions stretching from the antigorite-amesite line (Pauling's structural formula for chlorites) towards kaolinite (see fig. 42a).

* Because the true symmetry is uncertain Brindley (in Brown 1960) prefers to use the term orthogonal rather than orthorhombic or orthohexagonal.

B. X-RAY DATA FOR CHAMOSITES FROM THE CLEVELAND IRONSTONES

Previous X-ray measurements on chamosites from the Pecten Seam (Bannister in Hallimond 1939, p. 462 fig. 4) and Main Seam (Bannister in Whitehead et al. 1952, p. 20-22) suggested:-

(i) the presence of 14Å chamosite rather than 7Å, in contradistinction to other ironstone chamosites investigated by Youell (1955).

(ii) the possibility of variation between ooliths and matrix.

The present samples were therefore selected in order to test the validity of the first and to show the extent of variation between chamosites with different modes of occurrence, in ooliths, spastoliths and matrix.

Powder photographs were obtained with filtered Fe-K$^{\alpha}$ radiation after exposures of 18 hours at 30kV, 10mA, using a large Philips Debije Scherrer Camera with small collimators. The diffractograms were prepared subsequently using a Joyce microdensitometer.

1. Ooliths

a) Preparation

Because of their concentric structure it was possible to obtain diffraction patterns from single ooliths selected under a binocular microscope without grinding.

b) Main Seam (Table 9 and figs. 41)

Two types of oolith were selected from this seam:-

(i) 306- olive green ooliths ~~(page~~

FIG. 41. X-RAY POWDER DATA FOR MONOCLINIC AND ORTHOGONAL CHAMOSITES.

Orthogonal Structure			306		450		451 (462)		Monoclinic Structure		
I(calc.)	hkl	d(Å)	d(Å)	I/I	d(Å)	I/I	d(Å)	I/I	d(Å)	hkl	I(calc.)
70	001	7.026	6.87	86	7.05	98	7.08	100	7.026	001	70
21	020	4.657	4.66	26	4.60	21	4.66	12	4.657	020	7
									4.559	110	14
						6	4.26	4	4.274	$1\bar{1}1$	11
25	021	3.880			3.90	7	3.91	6	3.880	021	8
38	002	3.513	3.50	57	3.52	63	3.52	50	3.513	002	38
									3.492	111	6
									3.132	$11\bar{2}$	4
7	002	2.804	2.80	?	2.80	7			2.804	022	3
8	200	2.688	2.69	11	2.69	8	2.67	14	2.679	$20\bar{1}$	13
									2.669	130	19
88	201	2.511	2.51	100	2.51	100	2.51	43			
									2.405	$20\bar{2}$	27
					2.41	4	2.39	16	2.396	131	55
									2.271	201	4
									2.270	$13\bar{2}$	9
2	041	2.210									
48	202	2.135	2.14	48	2.14	42	2.14	22			
							2.01	5	2.012	$20\bar{3}$	8
									2.005	132	15
3	042	1.941									
							1.89	7	1.898	$13\bar{3}$	5
									1.884	202	3
30	203	1.766	1.77	35	1.77	29	1.77	15			
2	240	1.760									
3	241	1.707									
							1.66	12	1.664	$20\bar{4}$	6
									1.658	133	12
2	043	1.651									
									1.562	$13\bar{4}$	13
									1.561	203	5
									1.558	$33\bar{1}$	14
21	060	1.552	1.55	53	1.55	26	1.55	17	1.552	060	7
									1.521	$33\bar{2}$	3
									1.520	330	5
11	061	1.516	1.52	24	1.52	14	1.52	11	1.516	061	4
23	204	1.471	1.465	24	1.470	18	1.471	6			
									1.425	$33\bar{3}$	2
									1.422	331	2
6	062	1.420	1.420	11	1.421	7	1.421	6	1.420	062	2
3	005	1.405							1.405	005	3
2	044	1.403									
									1.347	$40\bar{1}$	1
2	400	1.344					1.343		1.343	$26\bar{1}$	5
14	401	1.320	1.320		1.320						
							1.317		1.314	$13\bar{5}$	5
									1.314	204	3

d(Å) spacings for Monoclinic and Orthogonal chamosites calculated on the basis of:-

Monoclinic cell: a 5.40, b 9.314, c sin β 7.026Å, β 104.5°.

Orthogonal cell: a 5.38, b 9.314, c 7.026Å.

See Brindley 1951a, p. 515.

(ii) 274- white ooliths, from which there was reason to believe iron might have been leached during the formation of siderite replacement spars ~~(page~~

Although varying slightly in degree of crystallinity the nine samples examined, regardless of colour, gave virtually identical powder photographs (table 9 ~~and figs.~~). In ~~table~~ figure 41 the observed spacings and intensities for sample 306 are compared with data calculated for orthogonal chamosite (Brindley 1951b, p.516), and show excellent agreement. The following facts were noted:-

(i) there is no suggestion of a 14Å reflection.

(ii) all the lines and their relative intensities are predicted by an orthogonal unit cell; no lines diagnostic of a monoclinic cell occur. ~~(cf. table~~

(iii) all the peaks are sharp with the exception of the 020 peak (4.66Å) the diffuseness of which is taken to indicate random displacements of layers parallel to the y-axis by integral multiples of $^{y}/3$, a type of disorder common among layer silicates (Brindley 1951b, p. 518).

(iv) since all the reflections labelled 201 are sharp (2.51, 2.14, 1.77, 1.47Å), there can be no disorder parallel to the x-axis. (cf. Brindley 1951b, p. 519).

It is therefore concluded that ooliths from the Main Seam consist of well ordered, orthogonal septechamosite apparently without admixture of monoclinic material (cf. Brindley and Youell 1953, p. 60). The whiteness of many ooliths is attributed to the presence of small quantities of opal (Dunham in Whitehead et al. 1952, p. 24), possibly released during sideritisation (pages 235-238) but appears to have little effect upon the diffraction patterns.

c) Two Foot Seam (Table 9) ~~and fig~~.

Ooliths from the Two Foot Seam (e.g. specimen 449) produced similar patterns to those from the Main Seam but with the following differences:-

(i) an additional line occurs at 2.41Å which is not predicted by an orthogonal unit cell, but which coincides with the strongest reflection attributed solely to a monoclinic cell ($20\bar{2}$, 131); compare table

(ii) at the same time the intensity of the 201 reflections, which are entirely orthogonal, is reduced; the 200 reflection at 2.67Å is an exception, being common to both cells.

Despite the weakening of the 201 reflections there is no suggestion of x-axis disorder so that like the previous chamosite this is regarded as a well ordered orthogonal septechamosite but with some admixture of monoclinic material. Comparison with Brindley (1951b, table VI., p. 518) suggests a combination of 10 percent monoclinic with 90 percent orthogonal.

d) Raisdale Seam (Table 9) ~~and fig.~~

An oolith from the Raisdale Seam (specimen 450) produced the clearest of all the powder photographs. Again it proves to be a well ordered orthogonal septechamosite with a small percentage of monoclinic material, but less than in the Two Foot ooliths.

e) Avicula Seam (Table 9) and fig. 41)

Ooliths from the Avicula Seam (e.g. specimen 452) gave poor photographs partly due to poor crystallinity and partly as a result of replacement by phosphate. However, the majority of orthogonal lines are present including the 201 series, without interference from monoclinic lines. Again there was no sign of a 14Å reflection.

f) The effects of grinding ooliths

Because, to obtain specimens of chamosite from spastolithic ooliths and from the matrix, either scraping or grinding was necessary, a powder photograph was taken in order to determine the effect of using lightly crushed powders rather than single ooliths. Seven ooliths identical with specimen 306 were powdered for this purpose (specimen 460). A comparison between columns 2 and 3 of table 9 shows that this method of preparation is liable to:- (i) enhance the basal reflection (001) and (ii) weaken certain other reflections and especially the important 201 series. These changes are probably simply a matter of preferred orientation since crushing does not appear to result in disordering. Nevertheless, it is evident that the data to follow will not be completely comparable with that presented for single ooliths. In practice it was found that scraped samples provided better patterns than crushed, so that wherever possible grinding was avoided (compare columns 10 and 11 table 9).

Table 9

	d(Å) for 450	orthogonal chamosites						disordered orthogonal chamosites			33M: 67Orth. chamosite		d(Å) for 451	
		274	306	460	449	450	452	563	459	454	451	462		
	7.05	100	86	100	100	98	100	100	100	100	100	100	7.08	
	4.60	25	26	22	20	21	34	25	22	21	13	12	4.66	
								8			4		4.26	
	3.90					7					6	6	3.91	
	3.52	67	57	46	61	63	63	49	49	48	26	50	3.52	
	2.80	13	?	14	14	7	?		?					
	2.69	13	11	16	14	8	38	23	15	18	15	14	2.67	*
*	2.51	100	100	56	61	100	100	26	28	28	18	43		
					9	4			15	17	14	16	2.39	*
*	2.14	53	48	19	26	42	42	5	12	4	5	22		
											3	5	2.01	*
											5	7	1.89	*
*	1.77	48	35	14	19	29	25	7	9	10	5	15	1.77	
											4	12	1.66	*
	1.55	40	53	27	31	26	46	31	24	28	15	17	1.55	
	1.52	23	24	13	12	14	25	13	13	13	10	11	1.52	
*	1.471	44	24	11	19	18	21				3	6		
	1.421	19	11	8	9	7	21	7	5	10	5	6	1.421	

2. Matrix

Sample 563 (table 9) ~~fig.)~~ was scraped from the green chamositic matrix of the Upleatham facies of the Main Seam, and differs distinctly from all the patterns described previously. The mineral is still essentially an orthogonal septechamosite, although the enhanced intensity of the reflection at 2.67Å may indicate the presence of some monoclinic material. By comparison the remainder of the 201 series is both weak and diffuse. The 201 line at 2.51Å is better described as a band head and extends to a spacing of about 2.38Å; to the vicinity of the $20\bar{2}$, 131 monoclinic line. Even making allowance for the effects of preferred orientation the intensity of this line, and of the succeeding lines 202 (2.14Å) and 203 (1.77Å), is greatly reduced; 204 (1.47Å) is absent altogether. The diffuseness of these lines is similar to that noted for the 020 reflection (4.6Å), and according to Youell (1955) arises from a similar cause; namely from disorder, this time corresponding to random $^{x}/3$ displacement of layers parallel to the x axis (compare page 400 iii)

3. Spastolithic oolites (Table 9) ~~and figs.~~

a) Preparation

The main difficulty in dealing with spastolithic material was that of obtaining homogeneous samples; of necessity the powder photographs show the superimposed effects of chamosite derived not only from numerous ooliths but also from the matrix. Samples 459, 454 and 451 were obtained after grinding, while sample 462 was obtained by scraping.

Various impurities were encountered including siderite, calcite, goethite and quartz but not in sufficient quantities to obscure the chamosite reflections.

b) Samples 459 and 454 were derived from lenses of total spastolithisation from the Main Seam and Black Hard respectively ~~(pages~~
Thin sections show a small percentage of chamosite mud between the ooliths but suggest that the samples contain at least 90 percent oolitic chamosite.

In the light of this it is surprising to find that these spastolithic rocks bear a closer affinity to the X-ray patterns produced by the matrix than to the ooliths (see table 9) ~~and figs~~
This is chiefly illustrated by the 201 reflections; the 201 reflection (2.51Å) stands at the head of a diffuse band extending to 2.40Å where the monoclinic line $20\bar{2}$, 131 occurs; the 202 (2.14Å) and 203 (1.77Å) reflections are weak and diffuse and the 204 line (1.47Å) is absent. By comparison with all the previous samples the intensity of the line at 2.40Å indicates a higher content of monoclinic material, but none of the lower order lines attributable to this cell occur.

There is insufficient matrix in these samples to explain the x-axis disorder entirely and it is therefore concluded that disorder occurs in the ooliths as well as in the matrix.

c) Samples 451 and 462 (table 9) ~~and figs.)~~ were prepared from a similar rock to the above from the Avicula Seam by grinding and scraping respectively. However they differ in containing rather more matrix (about 20 percent) which in addition has undergone recrystallisation to radiating acicular bundles of chamosite, an occurrence which is unique to this horizon. Even after lines resulting from impurities were removed it was clear that these chamosites were characterised by extra lines not observed in the other samples. These lines occurred at 4.26, 2.01, 1.89 and 1.66Å and are all predicted by a monoclinic unit cell. In addition the important monoclinic line at 2.39Å was present, while the 201 series of orthogonal lines was weak and diffuse in some cases, and particularly in specimen 451 which underwent grinding. The observed intensities for sample 462, which was not subjected to grinding, suggest a mixture of 33 percent monoclinic with 67 percent orthogonal material, closely analogous to the Ayrshire Chamosite examined by Brindley (1951b, table VI, p. 518). Bearing in mind the unusual spherulitic habit of the recrystallised matrix it seems probable that the development of the monoclinic chamosite is associated with this stage of regrowth.

C. CONCLUSIONS

1. Septechamosite

There can be no doubt that the green mineral which occurs in the matrix and ooliths of the Cleveland Ironstones is a septechamosite; no 14Å line was encountered in any of the samples examined, and the 4.60-4.66Å line is wrongly positioned for a chlorite 003 reflection (see Brindley 1951b, p. 511). In addition differential thermal analyses indicate one main stage in the breakdown of the mineral, corresponding

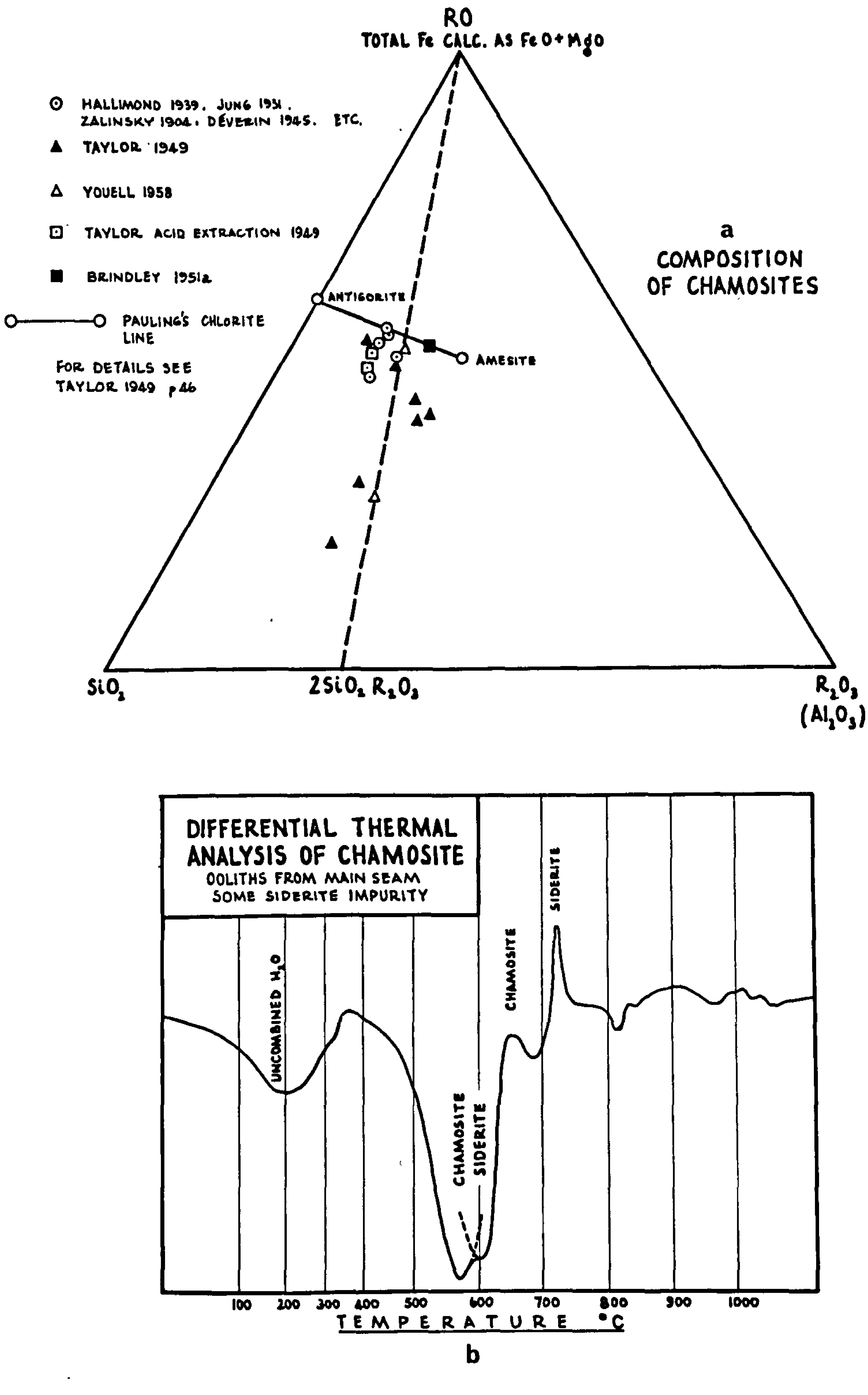

RO
TOTAL Fe CALC. AS FeO+MgO
HALLIMOND 1939, JUNG 1931, ZALINSKY 1904, DÉVERIN 1945. ETC.
TAYLOR 1949
YOUELL 1958
TAYLOR ACID EXTRACTION 1949
BRINDLEY 1951a
PAULING'S CHLORITE LINE
FOR DETAILS SEE TAYLOR 1949 p46
ANTIGORITE
AMESITE
a
COMPOSITION OF CHAMOSITES
SiO_2
$2SiO_2 R_2O_3$
R_2O_3
(Al_2O_3)
DIFFERENTIAL THERMAL ANALYSIS OF CHAMOSITE
OOLITHS FROM MAIN SEAM
SOME SIDERITE IMPURITY
UNCOMBINED H_2O
CHAMOSITE
SIDERITE
CHAMOSITE
SIDERITE
100
200
300
400
500
600
700
800
900
1000
TEMPERATURE °C
b

FIG. 42.

with an endothermic peak at about 550°C caused by:-

(i) the oxidation of ferrous iron to ferric

(ii) the dehydration of the brucite layer;

distinctly different from the two stage breakdown of the chlorites. (See fig. 42b and compare Brindley (1953, p.66-67) and Caillère and Hénin (p. 216 in Mackenzie 1957)).

In the light of this evidence the 14Å reflections recorded by Bannister (in Whitehead et al. p. 21-22) must be regarded as suspect. These chamosites therefore fall in line with other British Mesozoic chamosites investigated by Youell (1955) all of which were found to yield a 7Å structure.

Following the work of Nelson and Roy (1958) on the polymorphic transformation of septechlorites to normal chlorites, Pattinson (1964) and Bubenicek (1960) note that occurrences of normal chamosite are mainly restricted to Palaeozoic rocks while septechamosites occur in Mesozoic and Cainozoic rocks, suggesting that this transformation does in fact occur in nature.

2. <u>Crystal Structure and Disorder</u>

Brindley (1951a,b) explained the variation within the septechamosites in terms of an admixture of monoclinic with orthogonal chamosite, and the question now arises as to the nature of this mixture. There are several possibilities:-

(i) because of the difficulty of obtaining homogeneous samples it is possible that the two forms may co-exist separately; even within single ooliths the petrographic evidence indicates the presence of chamosite in different habits (pages 109-111)

(ii) since the two types differ only in the stacking of layers it is possible that they are intergrown as individual crystals or

(iii) form part of the same structure and result from varying degrees of x-axis disorder.

Brindley (op.cit. p. 519) was inclined to reject this third possibility because evidence for displacements parallel to the x-axis was lacking from his material, but Youell (1955, 1958) has demonstrated that this type of disorder does occur in ironstone septechamosites, and suggests that a complete transition exists from orthogonal types having no x/3 displacements, through disordered orthogonal types, to monoclinic types, with displacements between all layers.

The chamosites considered in the present work show precisely the same kind of variation as those studied by Brindley (ops.cit.) and Youell (ops.cit.), and at first sight appear to support Youell's contension; there appears to be a complete range from pure orthogonal chamosites (samples 274,306,460,452), through disordered orthogonal forms (samples 563,459,454) to forms yielding monoclinic admixtures of up to 33 percent (samples 462,451). According to Youell (1958) the 'modus operandi' for this variation is to be found in the substitution of aluminium for iron in the octahedral layer. Evaluated on the basis of 9(O + OH) ions he gives the following structural formulae for (i) high iron (ordered) and (ii) high alumina (disordered) orthogonal chamosites:-

(i) $$\underbrace{Al_{1.85}\ Fe^{3+}_{0.01}\ Fe^{2+}_{1.83}\ Mg_{0.23}}_{2.92}\ (Si_{1.33}\ Al_{0.67})\ O_{5.02}\ (OH)_{3.98}$$

(ii) $$\underbrace{Al_{1.09}\ Fe^{2+}_{1.30}\ Fe^{3+}_{0.12}\ Mg_{0.16}}_{2.67}\ (Si_{1.59}\ Al_{0.41})\ O_{5.15}\ (OH)_{3.85}$$

Without chemical analyses it is impossible to say where the Cleveland chamosites stand in relation to Youell's isomorphous series (fig. 42a) but the evidence at hand suggests that factors other than chemical composition may be responsible for the variation.

a) <u>Ooliths</u>

It is significant that all the undeformed ooliths examined gave patterns indicative of well ordered orthogonal chamosite, occasionally with some monoclinic admixture. Nevertheless despite the appearance of monoclinic lines in samples 450 and 449, there is no suggestion of disorder in the orthogonal lines, from which the writer concludes that the two forms occur separately possibly due to interlayering of orientated with unorientated chamosite in the oolitic envelope (pages 109-111)

b) <u>Matrix</u>

The disordered nature of the chamosite matrix in sample 563 may be attributed to the presence of high alumina chamosite, or to an abnormally high content of ferric iron (Youell 1955), but may equally well arise from the cryptocrystalline nature of the material.

c) Spastoliths

The disorder in the spastolithic ooliths appears to arise as a direct result of the spastolithisation process, and not from chemical variations. Lenses of spastolithic oolite may differ from the surrounding rock only in the manner of their grain support (page 158) and yet they show disordered structures, while neighbouring undeformed ooliths give well ordered patterns. It may well be, therefore, that spastolithisation is partly facilitated by dislocations within as well as without the chamosite crystals.

d) Recrystallisation

Judging from the evidence of specimens 462, 451, the monoclinic structure does not arise directly as a result of spastolithisation, but because of recrystallisation, which may of course be encouraged by the former. It is possible that the monoclinic material in other samples and especially in the spastolithic ooliths (459, 454) may result from the same cause particularly in view of the increase in birefringence which results from deformation (page 162)

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